Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon

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Abstract

A comparison of fluvial terrace sequences from around the world, based on data collected as part of International Geoscience Programme (IGCP) Project No. 449, has revealed significant patterns. River terraces provide important records of uplift, which is essential for their formation, and of landscape evolution. Their cyclic formation, however, almost invariably seems to have been a response to climatic fluctuation. Sequences in the European core area of IGCP 449, which has the longest and most extensive research history, have been used as templates for worldwide comparison. There is evidence for a global acceleration of uplift at the time of, and perhaps in response to, the Mid-Pleistocene Revolution, when climatic fluctuation switched to 100 ky Milankovitch cycles. Terraces formed prior to this generally consist of wide aggradational sheets that probably each represent formation over several 41 ky cycles. Subsequently, river valleys became more steeply entrenched and terraces formed in response to the stronger 100 ky climatic forcing, in many cases at approximately one per cycle. This paper uses the new data resource to explore differences between records in different climate zones, between sequences with variable numbers of Middle-Late Pleistocene terraces and between systems in which the all-important incision event has occurred in different parts of climatic cycles. Key records discussed include European examples from the Rhine, Thames, Somme, Dniester, Dnieper, Don, Volga and Aguas; from Asia the Gediz (Turkey) and Orontes (Syria); from North America, the South Platte and Colorado; from South Africa the Vaal and Sundays; from Australia the Shoalhaven; and from South America, the Amazon, Paraguay and tributaries of the Colorado and Negro.

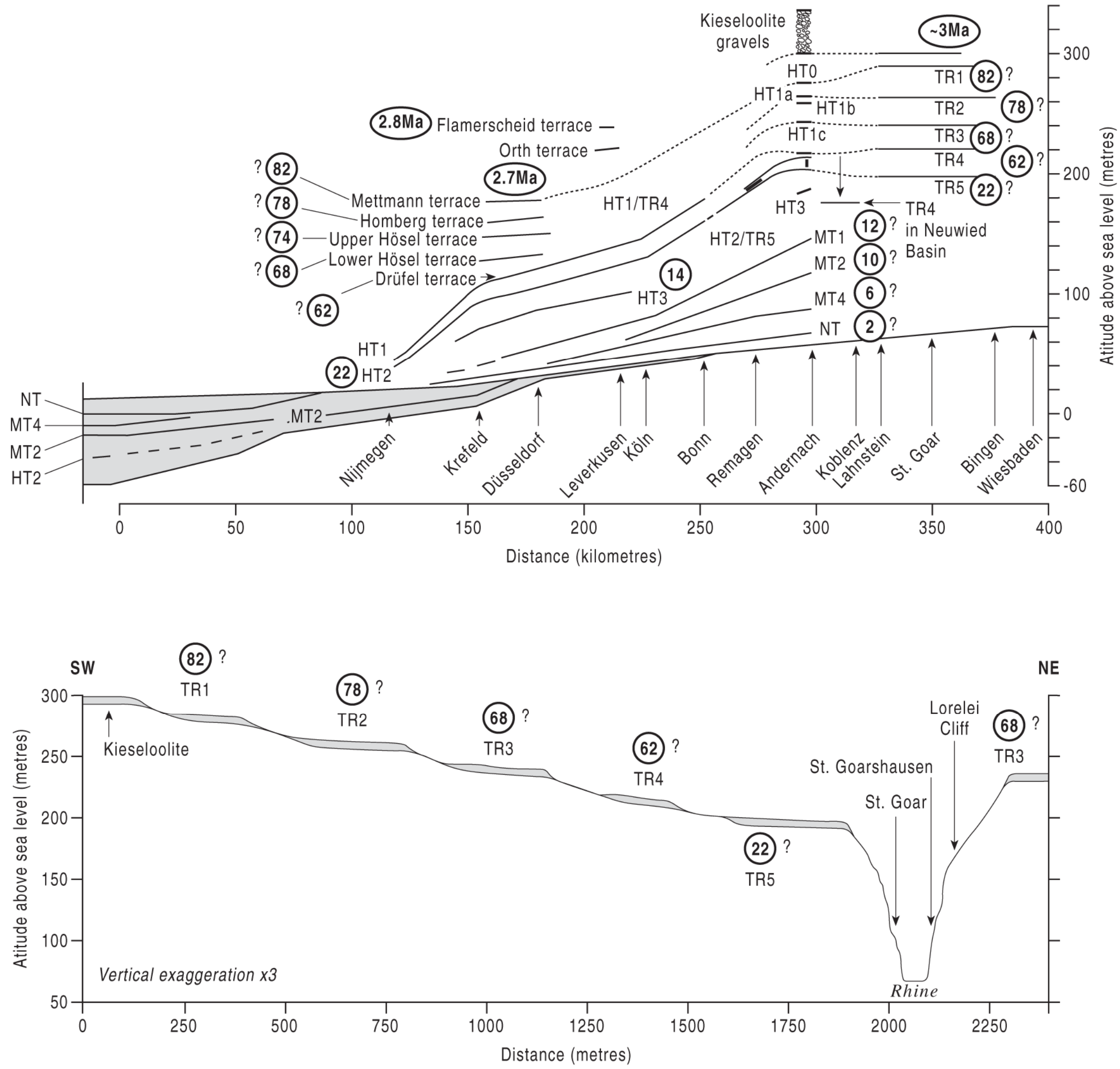
Keywords: river terrace, climatic fluctuation, uplift, fluvial incision, climatic geomorphology, crustal provinces

1. Introduction

This paper arises directly from the activities of International Geoscience Programme (IGCP) Project No. 449 (Global Correlation of Late Cenozoic Fluvial Deposits), which has compiled data on fluvial sedimentary records worldwide, enabling patterns and variations to be observed in the resultant databank. Fluvial sedimentary records can be divided into two main types, on the basis of preservation style: (1) stacks of deposits in superposition, although invariably with numerous hiatuses, and (2) terraced sequences, where the more important hiatuses have coincided with incision below the base level of the pre-existing deposits, into bedrock. This paper concerns the second of these types and will show, first, that they occur worldwide; second, that they have formed in response to climatic fluctuation; and third, that uplift is an essential requirement, with differences in uplift histories causing variations in terrace records between different areas and, in particular, different crustal provinces.

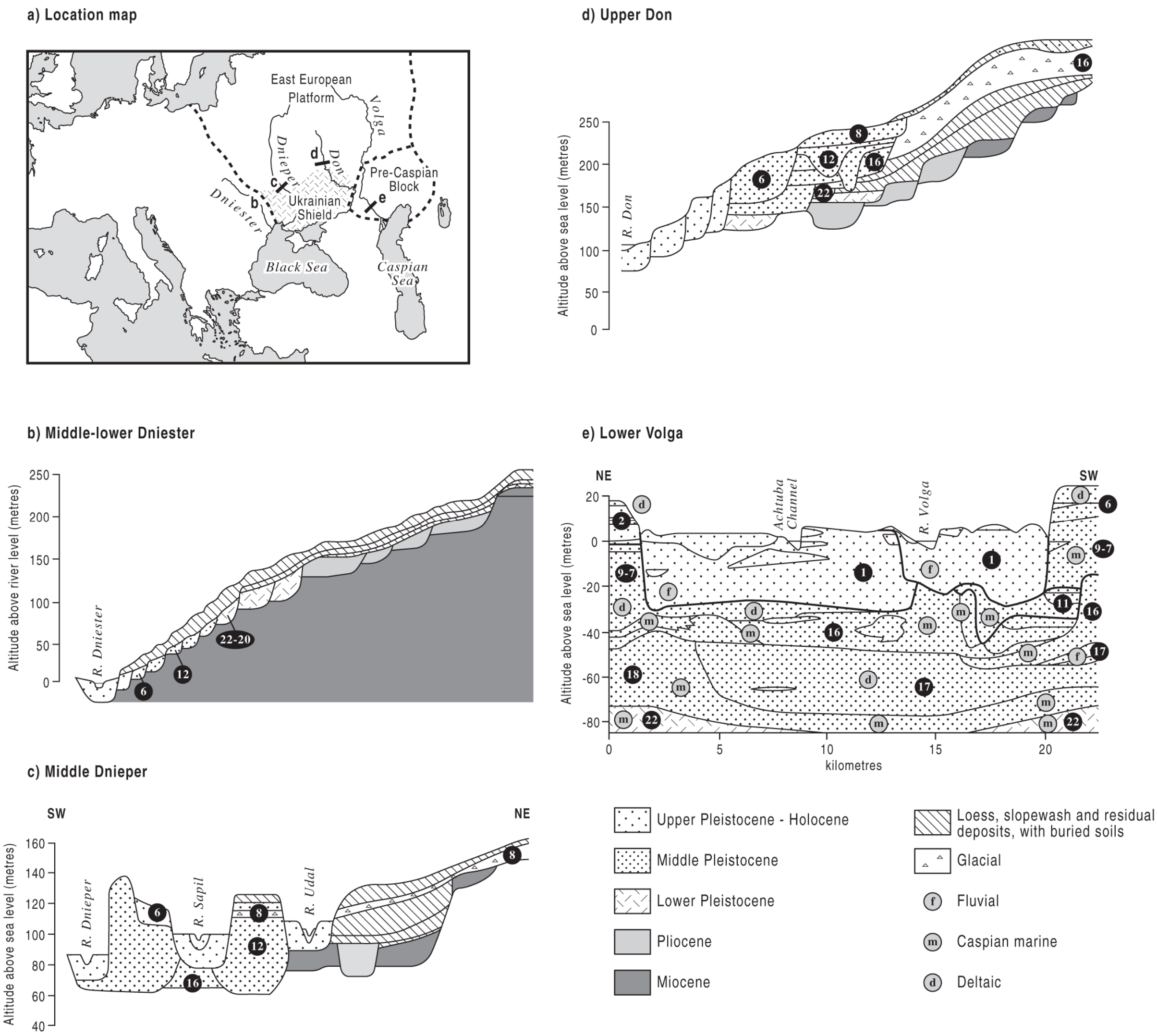
The staircases of aggradational river terraces that constitute this second type of record sometimes show wide separation, such that the fluvial deposits of each terrace level never come into contact with others in the terrace staircase. Alternatively, separation can be much less, such that in vertical extent each set of deposits overlaps those of the terraces immediately above and below within the staircase. Variations in degree of terrace separation and, indeed, between terraced and stacked sequences, can occur within a single fluvial system, either upstream - downstream (e.g. the Rhine sequence; Fig. 1) or in terms of variation through time (e.g. the Dniester, Dnieper and Don sequences; Fig. 2). The large dataset now assembled as a result of IGCP 449 allows such patterns to be investigated and evaluated, providing insights into their possible implications for understanding crustal and landscape evolution, key topics for follow-up project IGCP 518 (Fluvial sequences as evidence for landscape and climatic evolution in the Late Cenozoic).

Fig. 1



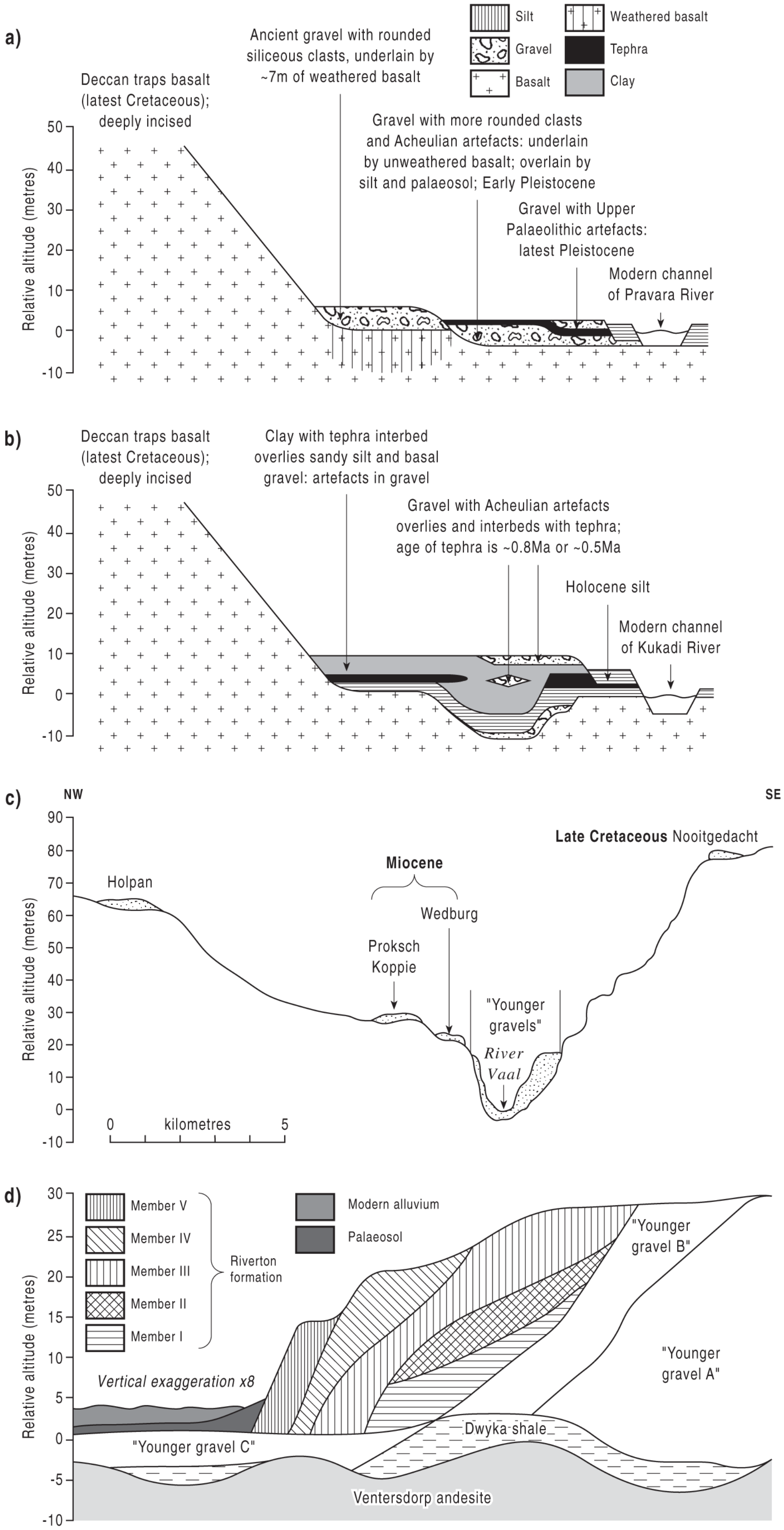
River terrace formation in areas remote from lithospheric plate boundaries has often been attributed to base-level fluctuation, driven by the rising and falling of global sea level in response to Quaternary climatic fluctuation (McCave, 1969; Törnqvist, 1998; Karner and Marra, 1998; Blum and Straffin, 2001), with aggradation thought to have occurred when the lower reaches of rivers were inundated by interglacial marine transgressions and incision at times of falling sea-level. The role of that same climatic fluctuation in triggering the different fluvial activities seen in terrace records, particularly alternations between incision and sedimentation, has long been recognized (e.g. Zeuner, 1945; Wymer, 1968; Bourdier, 1968, 1974; Antoine, 1994; Bridgland, 1994, 2000) and has been implicated as the driving force behind terrace generation in areas remote from coastlines, where sea-level fluctuation seems unlikely to be influential (e.g., Tyráček, 1983; Bull and Kneupfer, 1987; Green and McGregor, 1987; Bull, 1991; Starkel, 2003). This mechanism fits well with the empirical evidence from fluvial sequences, even those nearer to coasts, which shows that much of the aggradation, especially of gravel, has taken place under cold-climate conditions (e.g. Rose and Allen, 1977; Green and McGregor, 1980; Gibbard, 1985; Vandenberghe, 1995), at times when base levels were low and rivers should, according to the 'received wisdom' of the base-level paradigm, have been incising into their valley floors.

Fig. 2



There is now a consensus that long-timescale terrace staircases are responses to, and therefore records of, regional uplift (e.g. Maddy, 1997; Antoine et al., 2000; Bridgland, 2000; van den Berg and van Hoof, 2001; Westaway et al., 2002, 2006a; cf. Kiden and Tornqvist, 1998). Key to this line of thinking is that subsidence gives rise to stacked sequences, that uplift gives rise to terrace staircases and that without vertical movement of the crust rivers continue to flow at more or less the same relative level. Recently areas of highly stable crust have been recognized in which exactly this last type of activity, or relative inactivity, has prevailed: Archaean cratons (Westaway et al., 2003; Fig. 3). Such areas include parts of peninsular India and southern Africa (Helgren, 1977, 1978; Mishra 1995; Westaway et al., 2003; Fig. 3). This is not negative evidence; these areas have ancient fluvial deposits at or near to valley-floor level, rather than tens of metres higher (contrast Fig. 3 with Fig. 2b). The explanation favoured by Westaway et al (2003) is that these cratonic areas have not experienced the typical uplift that has raised surface levels in areas of younger crust and that this is because Archaean cratonic crust lacks the mobile lower crustal layer thought to be present in other, younger, continental crust. This is a result of its low radiogenic heat production and relatively thick (up to ~400 km) underlying lithosphere. Younger continental crust typically reaches >350 °C at depth, the temperature threshold above which plastic flow can occur. In contrast, Archaean cratonic crust is thought to be brittle throughout, preventing lower crustal flow. Crustal loading and unloading, resulting indirectly from Quaternary climatic forcing (e.g. ice sheet formation and melting; fluctuating sea-level; erosion and sedimentation) is thought to induce flow of lower crustal material from beneath areas that are subsiding to beneath areas that are uplifting (cf. Westaway, 2001, 2002a,b). If crustal stability is indeed the explanation for such records as depicted in Figure 3, it is clear that areas with extensive terrace staircases cannot have been stable, as was long supposed (cf. Westaway et al., 2002). A complicating factor is that many cratonic regions lie within the tropical zone, where differences in geomorphological processes might also be anticipated (Büdel, 1977, 1982; see below).

Fig. 3


a)
Silt
Gravel
Basalt
Weathered basalt
Tephra
Clay
Deccan traps basalt (latest Cretaceous); deeply incised
Ancient gravel with rounded siliceous clasts, underlain by ~7m of weathered basalt
Gravel with more rounded clasts and Acheulian artefacts: underlain by unweathered basalt; overlain by silt and palaeosol; Early Pleistocene
Gravel with Upper Palaeolithic artefacts: latest Pleistocene
Modern channel of Pravara River
Relative altitude (metres)
b)
Deccan traps basalt (latest Cretaceous); deeply incised
Clay with tephra interbed overlies sandy silt and basal gravel: artefacts in gravel
Gravel with Acheulian artefacts overlies and interbeds with tephra; age of tephra is ~0.8Ma or ~0.5Ma
Holocene silt
Modern channel of Kukadi River
Relative altitude (metres)
c)
NW
SE
Late Cretaceous Nooitgedacht
Holpan
Miocene
Wedburg
Proksch Koppie
"Younger gravels"
River Vaal
0 kilometres 5
Relative altitude (metres)
d)
Member V
Member IV
Member III
Member II
Member I
Riverton formation
Modern alluvium
Palaeosol
"Younger gravel B"
"Younger gravel A"
Vertical exaggeration x8
"Younger gravel C"
Dwyka shale
Ventersdorp andesite
Relative altitude (metres)

Several modern researchers have identified Late Cenozoic uplift in many areas of Europe but have generally attributed it to plate tectonic activity, particularly as a consequence of compressive plate boundary forces causing 'buckling' of the continental lithosphere that can extend, in series of upward and downward 'ripples', for considerable distances (e.g., Nikishin et al., 1997; Cloetingh et al., 2005). This interpretation envisages the uplift of various parts of north-west Europe, as evidenced by river terraces, as a distant response to the collision between the African and Eurasian plates. It requires this entire area to be in compression, thus conflicting with evidence, such as normal faulting, that shows much of it to be in extension. It cannot explain uplift in continental areas that are unrelated to compressive plate boundaries, so the discovery of comparable terrace staircases in such areas would pose a significant problem for the theory (see below).

If it is accepted that surface uplift has been influential in producing the terrace sequences in areas of post-Archaean crust, the IGCP 449 dataset can then be explored to see whether different styles of terrace preservation can perhaps be related to rates and styles of uplift. A long-standing observation, of importance in understanding landscape evolution, is of immediate relevance here. It is well established that pre-Middle Pleistocene fluvial terraces are characterized by wide expanses of sediment that record significantly greater valley-floor widths than are seen today, whereas terraces formed in the last million years or so record steeper incision and the narrowing of valleys (e.g. Kukla, 1978; Maddy et al., 2000; Fig. 1b). This pattern has been attributed to accelerated uplift starting at ~900 ka (Kukla, 1975, 1977, 1978; Meyer and Stets, 1998; Westaway, 2002a). A similar pattern can now been recognized in areas of post-Archaean crust in every continent except Antarctica (cf. Westaway et al., 2003). The closeness in the timing of this change in uplift rates to the so-called 'Mid-Pleistocene Revolution', when Milankovitch forcing of climatic cyclicity changed from predominantly 41 ky, obliquity-driven cycles to 100 ky eccentricity-driven cycles, is unlikely to be coincidental; instead a coupling between climatic fluctuation and the driving of uplift through lower crustal flow has been invoked, related to increased erosion brought about by the greater severity of the 100 ky climatic cycles predominant since ~1 Ma (Westaway, 2002a). Being linked to crustal loading and unloading by ice sheets, sea-level change and erosion, climatic forcing of uplift can be expected to have intensified in response to the change to 100 ky cycles. It is thus a mechanism that can plausibly provide a linkage between Quaternary climate and landscape evolution.

2. Empirical evidence for climatic control of terrace formation

Some of the most detailed fluvial records in the world are found in Europe, particularly in regions between the maximum extents of the Pleistocene Alpine and Scandinavian ice sheets (e.g., Figs 4 and 5). Most of these sequences span the Middle and Late Pleistocene, many also include the Early Pleistocene and a few extend back in time to the Pliocene and Miocene. Within these sedimentary archives are clues about the relation between fluvial activity and climatic fluctuation, primarily where fossils are preserved within the fluvial sediments, since these are often excellent indicators of palaeoclimate. Also important is the growing databank of geochronology from fluvial archives, which, coupled with biostratigrapical evidence, demonstrates approximate 100 ky cyclicity in terrace formation in many rivers: i.e., in synchrony with the Milankovitch cycles since ~1 Ma. This is by no means universal, many sequences having fewer terraces than one per 100 ky cycle and some having more. There are also potentially important differences as to when within the climate cycle the all-important incision event, leading to terrace formation, has occurred. Based on evidence from the Lower Thames (Fig. 4), Bridgland (2000) placed the downcutting during cold-to-warm transitions, as indicated by the occurrence of interglacial sediments in basal situations within each terrace. In the River Avon (English Midlands), the similar basal situation of interglacial remnants within terraces (Maddy et al., 1991) led to the same interpretation (Bridgland et al., 2004a). In other valleys in the same region of NW Europe, however, interglacial preservation is at or near the tops of terrace ‘treads’, leading to the conclusion that the downcutting event has occurred at the warm-to-cold transition. The Somme (Antoine, 1994; Antoine et al., 2000, 2003, in press; Fig. 5) and the Moselle (Cordier et al. 2004, 2006) are examples of systems in which this style of record occurs. It is possible that systems with many more terraces than 100 ky cycles, such as the (now-drowned) River Solent of southern England, have seen terrace formation at both transition episodes (cf., Vandenberghe, 1995, this volume; Bridgland, 2001). However, it is perhaps equally likely that a response to Milankovitch substage fluctuation is instead indicated (Westaway et al., 2006a); more precise geochronology will be required to determine which. A modified version of the Bridgland (2000) climatic model for terrace formation is presented in Figure 6, in which the various possibilities are accommodated. Vertical pairing of closely spaced terraces (Fig. 6B) would, as noted by Bridgland (2001), be expected where downcutting has occurred at both the warming and cooling transition, since the relative shortness of interglacials would mean the highly unequal separation of these events by ~80 and 20ky, respectively. Steady and progressive uplift would therefore have led to a comparable inequality in terrace spacing; downcutting at cooling-transitions might, therefore, coincide with shallow incision that fails to reach bedrock, whereas that at the warming transition might be expected to be much deeper. Indeed, major incision at cooling transitions (Fig. 6C) would perhaps only be expected in situations where warming-transition incision has failed to occur, perhaps because systems are swamped with sediment from destabilized landscapes, negating the increases in discharge brought about by melting permafrost.

Fig. 4

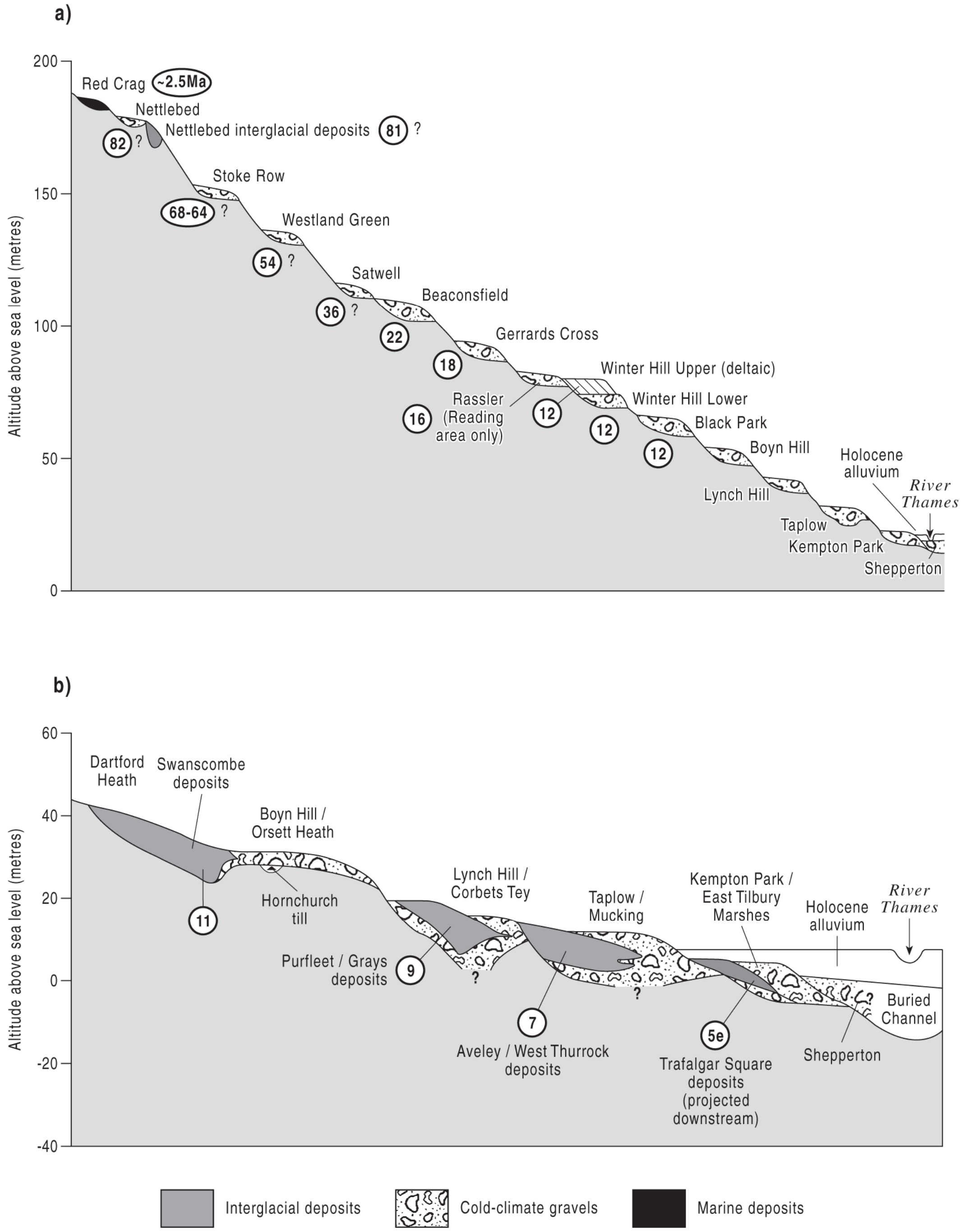

a)
200
150
100
50
0
Altitude above sea level (metres)
Red Crag
~2.5Ma
Nettlebed
82
?
Nettlebed interglacial deposits
81
?
Stoke Row
68-64
?
Westland Green
54
?
Satwell
36
?
Beaconsfield
22
Gerrards Cross
18
Winter Hill Upper (deltaic)
Rassler
(Reading
area only)
16
12
Winter Hill Lower
12
Black Park
12
Boyn Hill
Holocene
alluvium
River
Thames
Lynch Hill
Taplow
Kempton Park
Shepperton
b)
60
40
20
0
-20
-40
Altitude above sea level (metres)
Dartford
Heath
Swanscombe
deposits
Boyn Hill /
Orsett Heath
11
Hornchurch
till
Lynch Hill /
Corbets Tey
Purfleet / Grays
deposits
9
?
Taplow /
Mucking
7
?
Aveley / West Thurrock
deposits
Kempton Park /
East Tilbury
Marshes
Holocene
alluvium
River
Thames
5e
Trafalgar Square
deposits
(projected
downstream)
Shepperton
Buried
Channel
Interglacial deposits
Cold-climate gravels
Marine deposits

Fig. 5

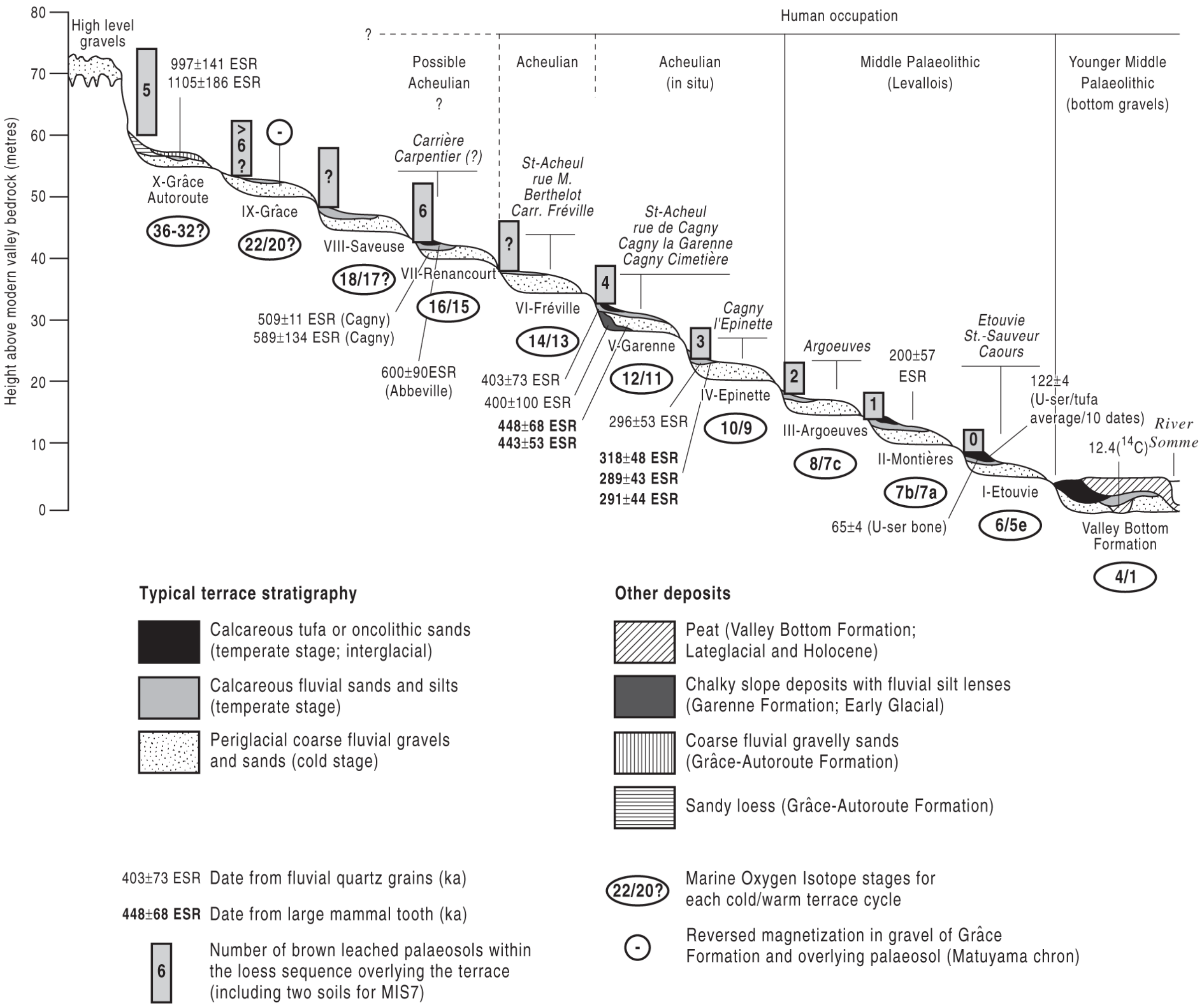
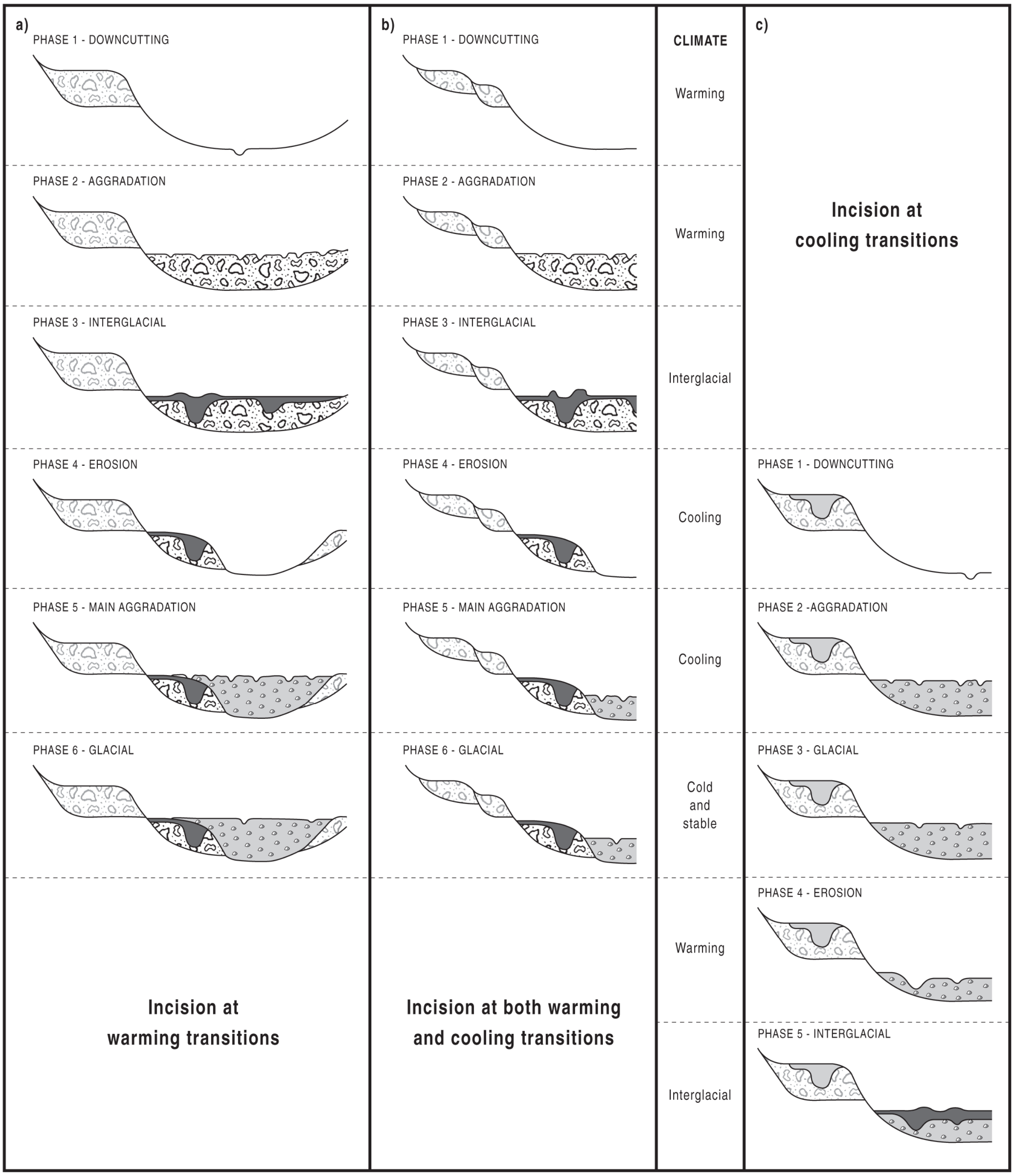

Human occupation
Possible Acheulian ?
Acheulian
Acheulian (in situ)
Middle Palaeolithic (Levallois)
Younger Middle Palaeolithic (bottom gravels)
Height above modern valley bedrock (metres)
High level gravels
997±141 ESR
1105±186 ESR
X-Grâce Autoroute
36-32?
IX-Grâce
22/20?
VIII-Saveuse
18/17?
Carrière Carpentier (?)
VII-Renancourt
16/15
509±11 ESR (Cagny)
589±134 ESR (Cagny)
600±90ESR (Abbeville)
St-Acheul rue M. Berthelot Carr. Fréville
VI-Fréville
14/13
403±73 ESR
400±100 ESR
448±68 ESR
443±53 ESR
St-Acheul rue de Cagny Cagny la Garenne Cagny Cimetière
V-Garenne
12/11
318±48 ESR
289±43 ESR
291±44 ESR
Cagny l'Epinette
IV-Epinette
10/9
296±53 ESR
Argoeuves
III-Argoeuves
8/7c
200±57 ESR
II-Montières
7b/7a
Etouvie St.-Sauveur Caours
I-Etouvie
6/5e
65±4 (U-ser bone)
122±4 (U-ser/tufa average/10 dates)
12.4(14C)
River Somme
Valley Bottom Formation
4/1
Typical terrace stratigraphy
Calcareous tufa or oncolithic sands (temperate stage; interglacial)
Calcareous fluvial sands and silts (temperate stage)
Periglacial coarse fluvial gravels and sands (cold stage)
Other deposits
Peat (Valley Bottom Formation; Lateglacial and Holocene)
Chalky slope deposits with fluvial silt lenses (Garenne Formation; Early Glacial)
Coarse fluvial gravelly sands (Grâce-Autoroute Formation)
Sandy loess (Grâce-Autoroute Formation)
403±73 ESR Date from fluvial quartz grains (ka)
448±68 ESR Date from large mammal tooth (ka)
Number of brown leached palaeosols within the loess sequence overlying the terrace (including two soils for MIS7)
22/20? Marine Oxygen Isotope stages for each cold/warm terrace cycle
Reversed magnetization in gravel of Grâce Formation and overlying palaeosol (Matuyama chron)

Fig. 6



3. Terrace staircases worldwide

As noted above, the occurrence of extensive terrace sequences in NW and central Europe is well established. In the latter area the recognition of long and complex Quaternary stratigraphies based on loess/soil sequences overlying river terrace deposits, in what was then Czechoslovakia (Kukla, 1975, 1977, 1978), paved the way for modern schemes in which terrestrial records are correlated with that from the deep oceans. IGCP 449 has documented important terrace sequences in the River Vltava, Czech Republic (Tyráček et al., 2004), and the Wipper and Ilm, central Germany (Mania, 1995; Schreve and Bridgland, 2002; Bridgland et al., 2004b). In the German examples there is excellent preservation of interglacial evidence within subaerial travertines that typically overlie cold-climate fluvial sediments, suggesting that here, as in the Somme, downcutting has occurred following interglacials.

3.1 Eastern Europe and the former Soviet Union

Although poorly known in the west, considerable research has been undertaken on fluvial sequences in the former Soviet Union. Summary review papers were therefore produced as part of IGCP 449, describing the sequences of the northern Black Sea and Caspian Sea rivers (Matoshko et al., 2002, 2004) and from rivers flowing to the Russian Arctic, namely the Kolyma (Patyk Kara and Postolenko, 2004) and Lena (Alekseev and Drouchits, 2004). The Black Sea and Caspian rivers, in particular, have records of great significance. Four south-flowing systems have been documented: the Dniester, Dnieper, Don and Volga (Matoshko et al., 2004; Fig. 2). Considerable variation is seen in the vertical disposition patterns of their sedimentary sequences, apparently in direct relation to the type of underlying crust. The dating of these various sequences makes use of biostratigraphical evidence from the sediments themselves, of overlying loess/palaeosol records, of sedimentary evidence in their lower reaches for the fluctuation of sea level and, in their upper reaches, for the direct influence of northern glaciation. Indeed, certain glaciations are named after the river basins in which they are best documented: the Don glaciation, correlated with MIS 16, and the Dnieper glaciation, generally attributed to MIS 8 (Matoshko et al., 2004).

The Dniester flows for ~700 km across Ukraine and Moldova, along the foreland basin of the Carpathian mountain range to the Black Sea, staying within the relatively young crust to the west of the East European Platform (Fig. 2a). As would be expected (see above), since it alone flows over 'normal' (i.e. relatively young and, therefore, relatively hot) continental crust, the Dniester has a terrace staircase recording continuous surface uplift, amounting to ~300 m in total, dating back to the Late Miocene (Fig. 2b). These terraces, 15 in total, consist of fluvial gravels, deposited under a braided regime during cold episodes, overlain by finer-grained deposits thought to represent temperate-stage overbank facies, which have yielded most of the age-control evidence. Again, therefore, this seems to suggest cooling-transition downcutting. The sequence can be divided into different phases of development based on clear variation in the style of terrace formation. Working backwards, the lowest seven terraces record incision by the Dniester in approximate synchrony with the 100 ky climatic cycles of the last million years, although the MIS 10 cycle is apparently missing (replaced by a wider vertical separation between the MIS 12 and MIS 8 terraces - see Fig. 2b). The earlier part of the sequence is made up of thicker and more extensive terrace deposits, probably representative of multiples of the shorter cycles that characterized the Miocene to Early Pleistocene, as in sequences in NW Europe, such as the Thames (Maddy et al., 2000; Westaway et al., 2002). The terrace staircase is inset into an aggradational (stacked) sequence of older fluvial deposits (the Balta Group) biostratigraphically dated to the Late Miocene (Fig. 2b).

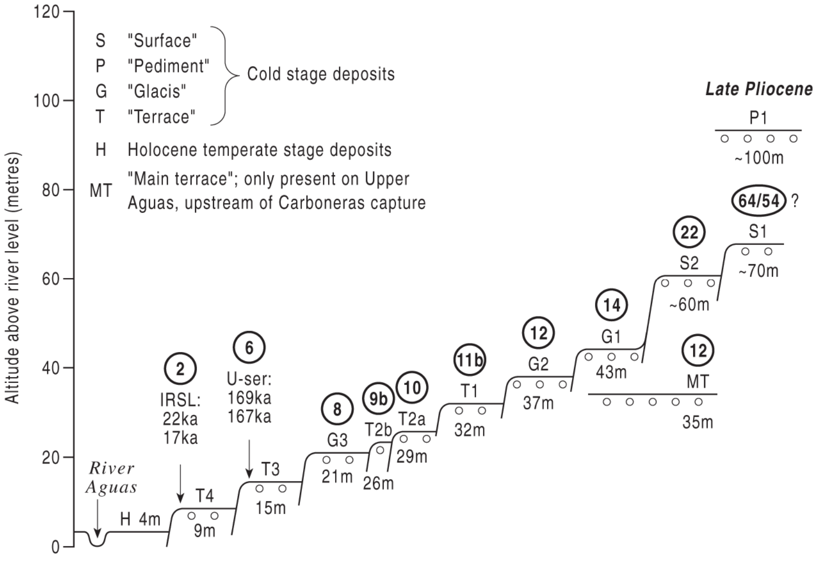
The Dnieper and Don, further east, also flow into the Black Sea, but their courses lie largely within the Ukrainian shield (Fig. 2a). In contrast to the 'classic staircase' of the Dniester, the Dnieper and Don sequences record a mix of incision and aggradation, presumably driven by alternating uplift and subsidence. Although rates of vertical crustal motion have at times been substantial (as indicated by differences in altitude of successive terraces; Fig. 2c and d), they were later cancelled out by reversals in the sense of motion, such that the total net movement indicated has never exceeded a few tens of metres. The fluvial sequences of the Ukrainian Shield (Fig. 2c, d) are certainly different from those of Archaean cratons but, with their indication of long-periodicity fluctuation between uplift and subsidence (producing no great net vertical change over Quaternary timescales), they also differ considerably from those typical of younger crust. The Early Proterozoic crust of this shield is intermediate in terms of age and thermal state between the Archaean and the near-ubiquitous younger crustal types and might therefore include a thin mobile lower-crustal layer.

The Volga, even further east, flows into the landlocked Caspian Sea along a course that lies in part within the East European Platform and in part within the Pre-Caspian Block, north of the Caspian Sea. The Pre-Caspian Block represents crustal basement of unknown origin (e.g., Nikishin et al., 1996), which is thought to have accreted against the SE margin of the East European Platform in the Late Proterozoic; drilling has reached latest Proterozoic (Vendian) sediments but not the underlying basement. This crust is evidently strong, since no significant deformation has occurred throughout the Phanerozoic. It has been suggested that it is a trapped fragment of oceanic lithosphere (cf. Şengör et al., 1993), overlain by sufficient sediment to create a subaerial land surface. Such oceanic crust can be presumed to lack a mobile lower layer, thereby mimicking the high stability of Archaean cratons (cf. Westaway et al., 2003). Thus the Lower Volga sequence shows accumulation of sediments of different ages within a narrow height range relative to the altitude of the modern river (Fig. 2e), indicative of little net vertical movement since the Early Pleistocene.

3.2 Mediterranean rivers

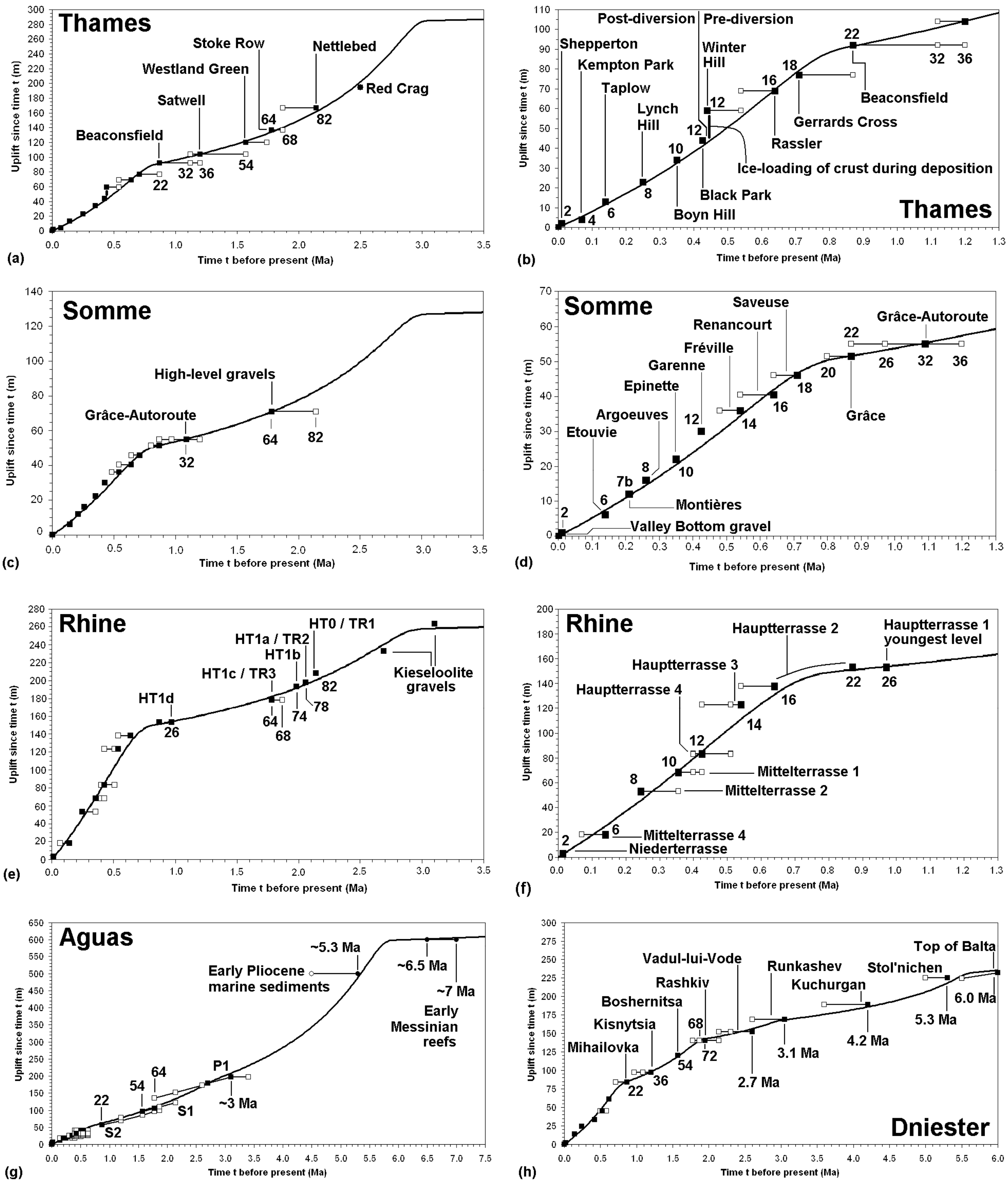
Turning to a warm temperate region, generally beyond the reach of Quaternary glaciation, two example systems from opposite ends of the Mediterranean, both receiving recent attention related to IGCP 449, will be reviewed. The first is the River Aguas, which drains the Late Cenozoic Sorbas and Vera Basins of SE Spain, and the second is the River Orontes of western Syria. The basins drained by the Aguas record marine conditions until the Early Pliocene. broken only during the Messinian salinity crisis, followed by fluvial environments thereafter (Harvey and Wells, 1987; Stokes and Mather, 2000; Schulte, 2002; Mather and Stokes, 2003; Braga et al., 2003). In the SW Vera Basin, Early Messinian reefs (pre-dating the salinity crisis; age ~7-6.5 Ma) crop out at ~600 m a.s.l., whereas Early Pliocene marine sediments are found nearby at ~500 m a.s.l. (Braga et al., 2003). There has thus been significant uplift since the Messinian, at time-averaged rates of ~0.1 mm a^{-1}. This region forms the northern part of the convergent boundary zone between the African and Eurasian plates, which has led many authors to ascribe the uplift, and its effect on fluvial activity, to active tectonic processes (Harvey and Wells, 1987; Stokes and Mather, 2000; Schulte, 2002; Mather and Stokes, 2003). However, local rates of relative plate motion are very low, no more than a few millimetres per year (e.g., Westaway, 1990; DeMets et al., 1994), too little to have caused convergent crustal thickening sufficient to account for the observed uplift rates throughout a zone several hundred kilometres wide (cf. Mitchell and Westaway, 1999). Harvey and Wells (1987) interpreted this as evidence of epeirogenic (i.e., regional) uplift, onto which local effects of active faulting are superimposed, a view very similar to the ideas now emerging from other parts of the Mediterranean region (e.g., Mitchell and Westaway, 1999; Arger et al., 2000; Westaway et al., 2006b).

Fig. 7



The Aguas has a staircase of sub-parallel terraces, thought to span the period since the Middle Pliocene (Schulte, 2002; Fig. 7). Comparison of their heights above the modern valley floor with the altitudes of dated marine terraces on the nearby coast (Schulte, 2002) is an important aid in dating the Aguas sequence. Modelling the fluvial incision and causative uplift, on this basis, results in an estimate of the latter not significantly at variance with those in other regions of relatively young continental crust (Fig. 8), raising serious doubts about whether plate tectonic activity has any role in influencing this effect.

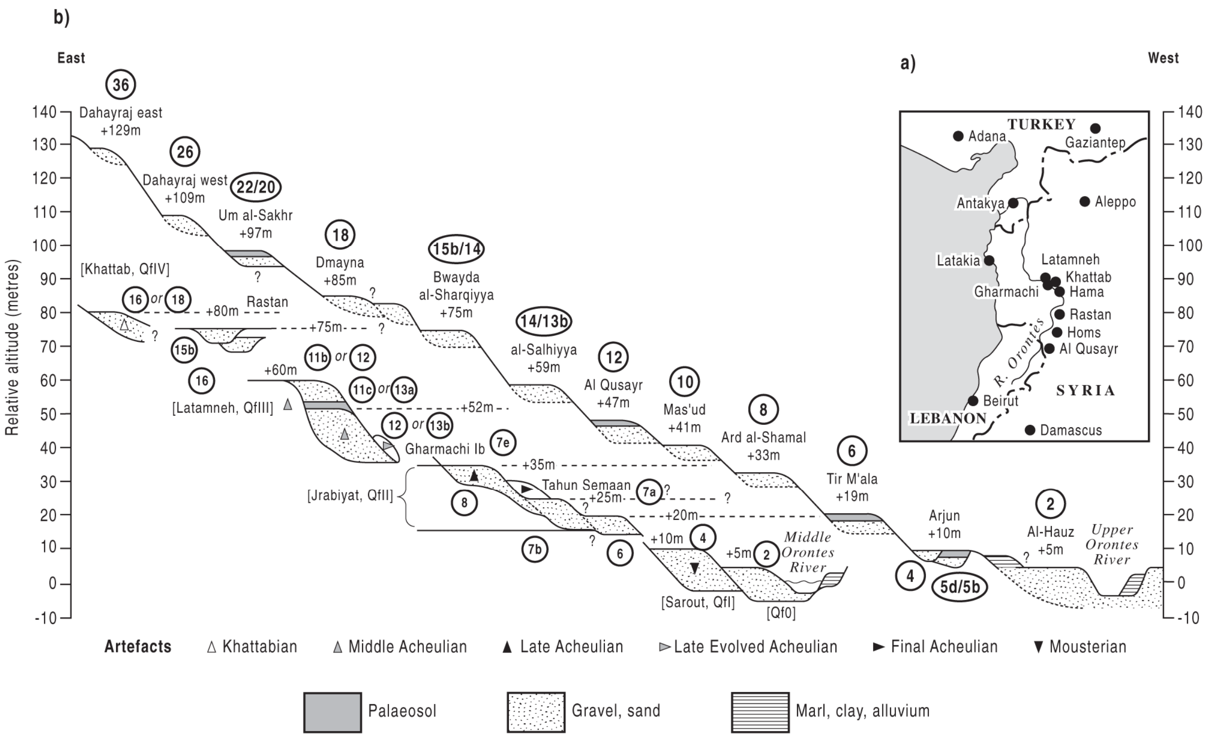
Fig. 8



In the eastern Mediterranean region terrace sequences are known from the Nile (Said, 1981), the Euphrates (Tyráček, 1987; Demir et al., 2004), the Jordan (Bar-Yosef, 1998), and many rivers in Turkey (Demir et al., 2004). Active crustal deformation in this region has led to some atypical fluvial records, with rivers affected by faulting and volcanism (e.g., Ozaner, 1992; Bunbury et al., 2001; Westaway et al., 2005, 2006b; Demir et al., 2004). Another eastern Mediterranean fluvial archive that has come to light during IGCP 449 is from the

Upper Orontes in Syria, studied by the present authors as part of long-running archaeological survey based on Homs (Bridgland et al., 2003). This continuing study seeks to relate Palaeolithic artefact assemblages from the area south of Homs to aggradational terraces of the Orontes, which have been newly mapped in a wide area to the east of the river (Fig. 9). Bridgland et al. (2003) reported a well-preserved staircase of at least 12 terraces in the 130 m above the river (Fig. 9), identified in the 2001 field season. Subsequent work in 2002 and 2003 has identified several more terraces up to ~200 m above the river.

Fig. 9



Data from the upper Orontes supplement previous findings from the Middle reach of the river (e.g. Besançon and Sanlaville, 1993; Dodonov et al., 1993), including the record from a key fossiliferous Palaeolithic site at Latamneh, ~80 km north of Homs (Fig. 9a). A mammalian assemblage from here can be ascribed to the mid-Middle Pleistocene; its combination of *Stephanorhinus hemitoechus* and *Megaloceros verticornis* has no exact parallel in Europe, where the former post-dates and the latter pre-dates MIS 12. This was used by Bridgland et al. (2003) to calibrate the age of their sequence from the Upper Orontes to around the time of this glacial (Fig. 9b). A further constraint is provided by the time of eruption of the latest Miocene Homs Basalt, which blocked any pre-existing drainage in this region; following this eruption the river has incised by ~400 m (Bridgland et al., 2003). Again the amounts of uplift indicated are comparable with post-Archaean crust remote from plate boundaries, suggesting that no special effect applies to the Orontes related to its situation in the (active) Dead Sea Fault Zone (the active boundary zone between the African and Arabian plates; cf. Westaway, 2004). Localized uplift related to this fault zone has been recognized, but is concentrated to the west rather than the east, where the Orontes flows (cf. Westaway, 2004).

Another Eastern Mediterranean river system with a long-timescale record is the Gediz in western Turkey. This system is situated sufficiently far from any major active faults for it to be clear that it has responded to regional uplift, not local tectonic effects. In the vicinity of the Kula Quaternary volcanic field, this river has produced a staircase of terraces indicating ~400 m of incision since the Pliocene (e.g., Westaway et al., 2004, 2006b; Maddy et al., 2005). Basalt lavas have provided both excellent preservation of underlying Gediz deposits and, using K/Ar and Ar/Ar techniques, a means of dating the fluvial activity. In particular, there are 11 high-level terraces (~200-140 m above the modern Gediz) that, from the available dating of the overlying basalt and from uplift-modelling constraints, may represent successive 41 ky (Early Pleistocene) Milankovitch cycles (Maddy et al., 2005; Westaway et al., 2006b).

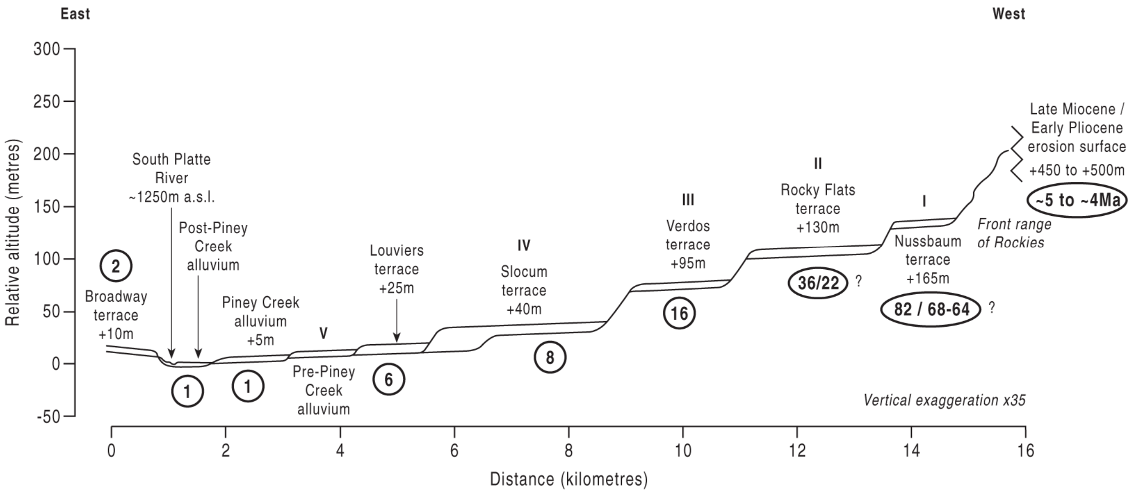
Plentiful supplementary evidence is available in support of the notion that the relatively young continental crust in the Mediterranean region has behaved in a similar way to that (of post-Archaean age) elsewhere in the world. To the terrace sequences of the Nile and Euphrates (already mentioned) can be added, as evidence of surface uplift, the terraces of the Kebir and the occurrence of raised beaches along the Syrian and Lebanese coasts. Around Latakia, northern Syria (Fig. 9a), marine terraces alternate with the Kebir terraces (Besançon et al., 1978; Besançon and Sanlaville, 1984), indicating that the river terraces did not form during interglacial high-stands (e.g., Copeland and Hours, 1993). This is important in that it suggests that fluvial aggradation occurred during cold stages, as in the areas further north. Whether temperature fluctuation or variation in precipitation is the key forcing factor for climatic triggering of terrace formation in these warmer regions remains uncertain, however. The effects of aridity/precipitation fluctuations on fluvial discharge and sediment load might be comparable with those of temperature; like temperature cycles, humidity fluctuations would be expected to operate both directly and indirectly, the latter by means of their influence on vegetation density and, thereby, on slope stability (see below). The two types of cycle are likely to be inter-related (e.g. Rossignol-Strick, 1999) and their individual contributions difficult to resolve.

3.3 North America

In marked contrast to Europe, river terrace records have had limited prominence in North American Quaternary studies. The Mississippi terraces are well known, but there is a paucity of biostratigraphical control on their ages, dating having instead been achieved with reference to Laurentian glaciations, which have fed melt-water southwards into this river, and loess-soil sequences overlying the terraces (cf. Fisk, 1951; Saucier, 1996; Blum et al., 2000). North American rivers in areas within the zone of repeated Pleistocene glaciation have restricted records, with little evidence as old as Middle Pleistocene (e.g. Clet-Pellerin and Occhietti, 2000). Despite extending well south of the maximum glacial limits, the Lower Mississippi terrace sequence can be dated back only to the Middle Pleistocene (Blum et al., 2000; Blum and Straffin, 2001), but other systems in the southern part of the continent have records spanning the Late Cenozoic and sometimes even the whole of the Cenozoic. Notable amongst these is the Susquehanna (e.g., Pazzaglia and Gardner, 1994).

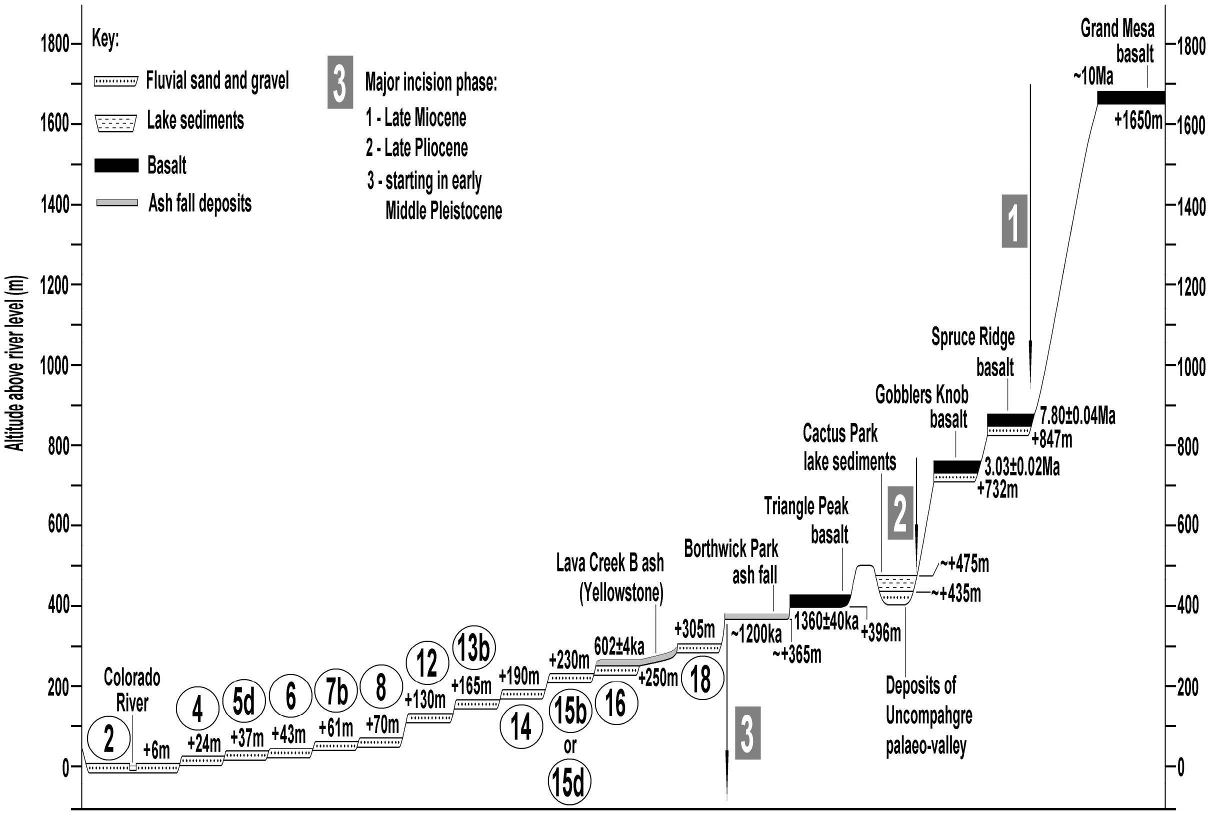
One of the best-documented North American records of uplift-driven fluvial incision comes from right-bank tributaries of the Missouri - Mississippi system that drain eastward from the Rocky Mountains across the central United States, a notable example being the River Platte (Fig. 10). This system consists of two principal affluents, both with notable terrace staircases. The South Platte flows through the city of Denver, Colorado, where it has incised by ~500 m into the Miocene / (?) Early Pliocene landscape (Fig. 10), whereas the North Platte flows across eastern Wyoming and western Nebraska, where it has formed a comparable terrace staircase within the High Plains (Reed et al., 1965; McMillan et al., 2002; Heller et al., 2003). There is every reason to suppose that, as elsewhere in the temperate latitudes, these terrace sequences have formed as a result of climatic forcing of fluvial activity set against a background of surface uplift (cf. McMillan et al., 2002). The sequences exemplified by Figure 10 imply terrace formation at a lower frequency than once per 100 ky Milankovitch cycle, with only the major climatic oscillations represented, as in certain European rivers (see above). The apparent absence of any MIS 12 terrace, also a notable feature of the Susquehanna sequence (Westaway, in press), is in marked contrast with European records.

Fig. 10



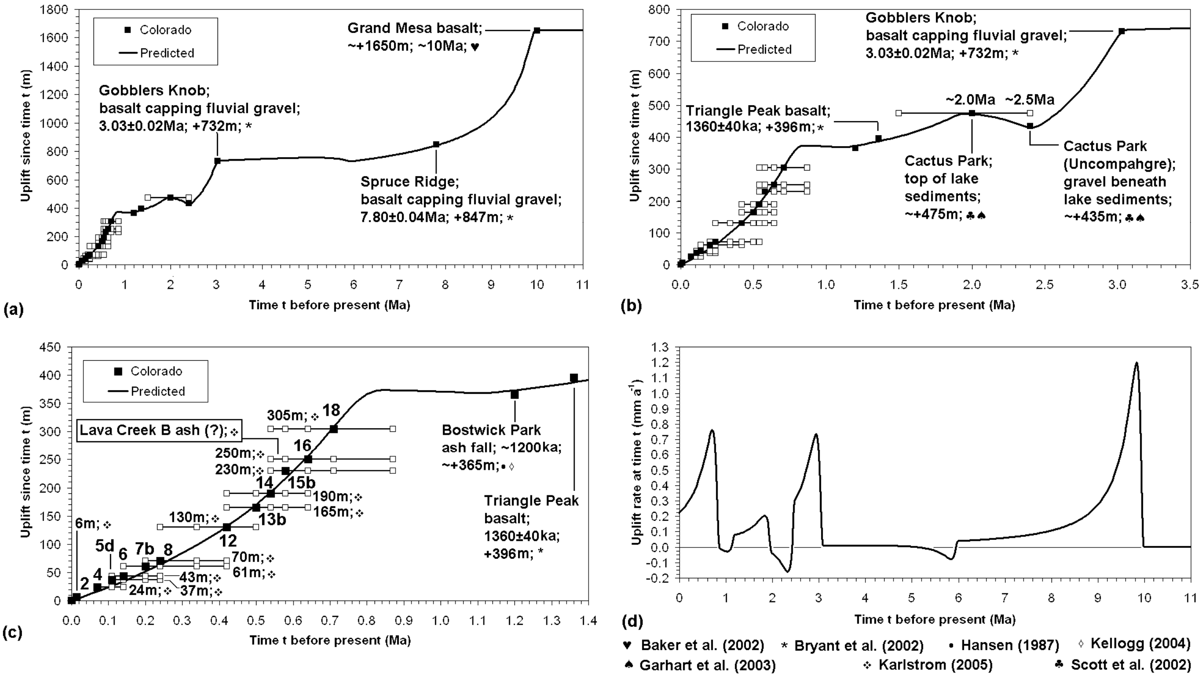
Dramatic Late Cenozoic fluvial incision has also been documented in western North America, the most famous example being the ~1500 m deep Grand Canyon of the River Colorado in Arizona. Time-averaged incision of this canyon has been calculated as ~0.1 mm a^{-1}, from its relation to dated Miocene volcanism (Damon et al., 1974). Along the canyon the amounts of incision show a general downstream decrease; for instance, the incision since ~500 ka has been ~260 m near the upstream end of the canyon in SE Utah (Garvin et al., 2005) but only ~30-50 m, ~200-300 km to the WSW in NW Arizona (e.g., Lucchitta et al., 2000; Pederson et al., 2002). However, the extent to which this results from the localized effects of vertical slip on active faults, rather than true regional-scale tapering in the regional uplift has yet to be determined (cf. Pederson et al., 2002, 2003; Hanks and Blair, 2003).

Fig. 11



The clearest evidence for the history of long-timescale incision by the Colorado system is derived from upstream of the Grand Canyon, in the Grand Valley region of western Colorado state, around Grand Junction (Fig. 11). This dataset represents localities up to ~150 km apart; there is thus the possibility that uplift histories and/or rheological properties of the crust have varied laterally (as for the Dnieper – see Fig. 2c caption); furthermore, there is evidence of some local variation in vertical motion associated with minor active faulting (e.g., Kellogg, 2004). A total of ~1650 m of fluvial incision is evident since the Middle Miocene (Fig. 11). The oldest evidence is provided by dating to ~10 Ma of the basalt cap of Grand Mesa, this basalt being thought to have flowed into a palaeo-valley occupied by the ancestral Colorado. Dramatic incision occurred down to the level of the next marker, the Spruce Ridge basalt, which is dated to ~7.8 Ma and caps fluvial gravel at 847 m above the river (Figs 11 and 12). Notable subsequent increases in rates of uplift and incision are evident around 3 Ma and 0.9 Ma (Fig. 12).

Fig. 12



3.4 Southern Africa

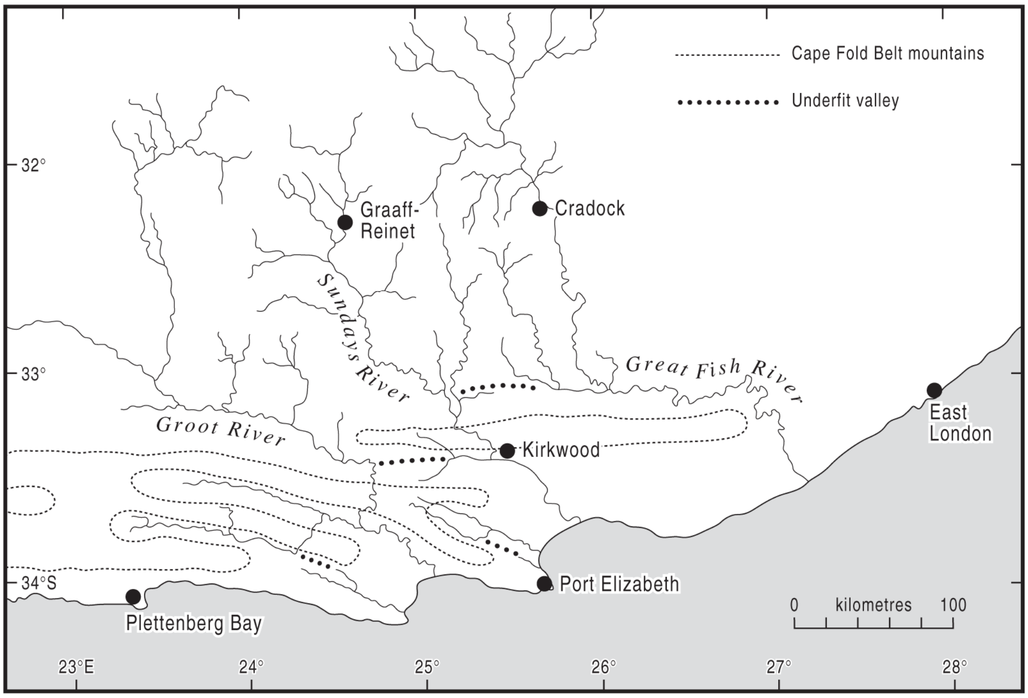
This is a temperate-climate region of the southern hemisphere in which the effects of Quaternary glacial - interglacial fluctuation would be expected to have left a record comparable to those in equivalent regions of the northern hemisphere; climatically, these would be the Mediterranean regions. Southern Africa has already featured above, in connection with the Archaean cratonic area at its core. This is drained by the Vaal, which has a Late Cenozoic fluvial sequence of restricted vertical range (Fig. 3d), starting with the Miocene Proksch Koppie and Wedburg gravels (Fig. 3c). The oldest Vaal gravel shown in Figure 3d, the 'Younger Gravel A', is of Pliocene – Early Pleistocene age, indicating no significant fluvial incision during the Quaternary in this craton. However, younger crust is also to be found in southern Africa, ranging in age from Early Proterozoic to Palaeozoic. A published fluvial record from outside the cratonic area, from the Sundays River in the Namaqua-Natal crustal province (Middle-Late Proterozoic) and the Cape Foldbelt (Palaeozoic), provides an important contrast with the Vaal.

The Sundays has, in its lower reaches, a well-developed terrace staircase (e.g., Hattingh, 1994; Hattingh and Goedhart, 1997; Hattingh and Rust, 1999; Fig. 13). The terraces remain subparallel across the transition between the Namaqua-Natal crustal province and the Cape

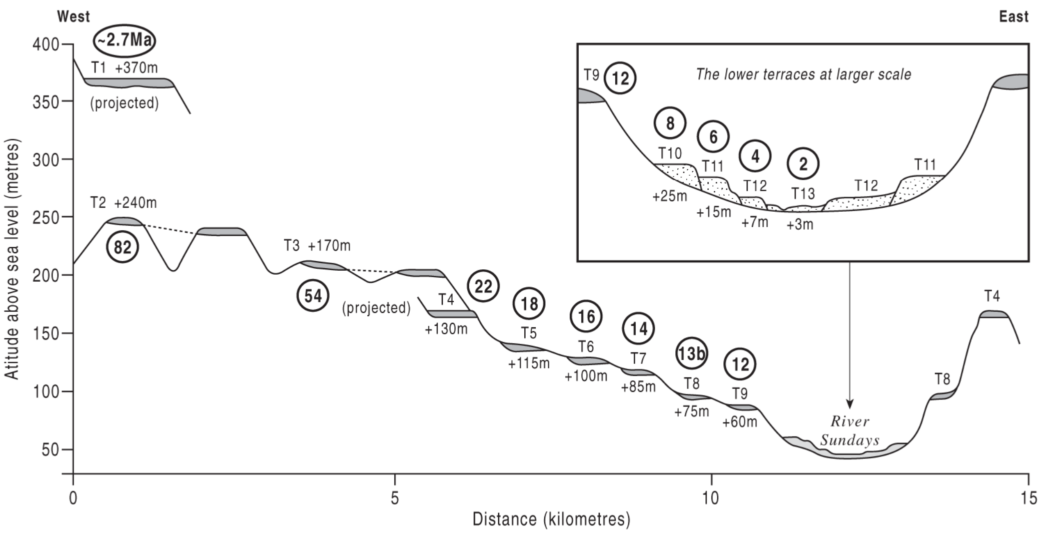
Foldbelt, suggesting that the uplift response within these crustal provinces has been similar. No direct age-control is available for any of the Sundays terraces, so it is necessary to estimate their ages based on relations with other datable deposits and by modelling the fluvial incision they record, the latter using the methodology of Westaway (2001; Westaway et al., 2002; Fig 14). Minimum-age dating control is provided by marine sediments at ~450 m a.s.l. near Kirkwood, which have been attributed to the Middle Pliocene (McMillan, 1990) and which pre-date the full Sundays sequence (Fig. 13). Taking the age of these marine sediments as ~3 Ma, a subsequent time-averaged uplift rate of ~0.15 mm a^{-1} is indicated. Assuming simple progressive uplift over this period, however, cannot provide a sensible explanation for the configuration of the terraces in the Sundays valley. Modelling a pulse of accelerated uplift in response to the Mid-Pleistocene Revolution, as is seen in well-dated sequences from other parts of the world (and demanded by the principles of lower crustal flow forcing - see above; Westaway et al., 2006b), provides a much better match for the Sundays terraces (Fig. 14). Indeed, it is also broadly consistent with the set of ages inferred by Maud (1968) for the staircase of marine terraces east of the Sundays estuary.

Fig. 13

a)

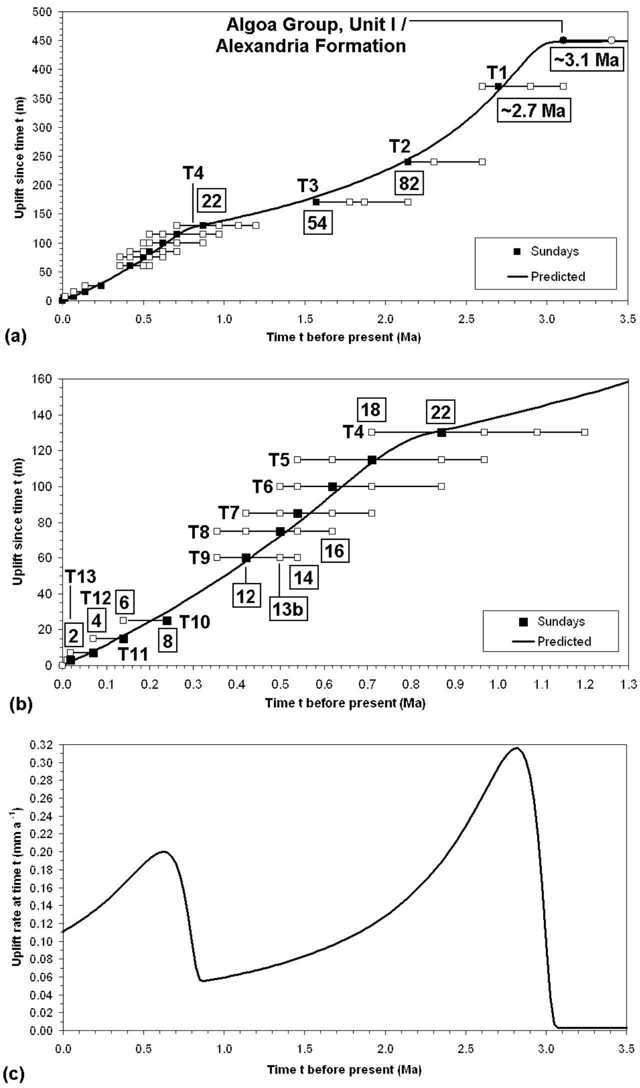


b)



It should be noted that this interpretation differs significantly from that proposed by Hattingh and Rust (1999). They adopted a different age model, after Le Roux (1989, 1990), in which the ~450 m marine deposits were attributed to the Late Miocene, rather than Middle Pliocene. In their view, Sundays terraces T1 to T9 formed in the Late Miocene and Pliocene, with only T10 to T13 assigned to the Pleistocene. Furthermore, in their view the fluvial incision resulted from global eustatic sea-level fall, not regional uplift; however, the idea that sea-level could have fallen by ~450 m since the Miocene (or Pliocene) is irreconcilable with the subsequent net increase in global ice volume. The alternative McMillan (1990) age model for the marine sediments, adopted here, has also been preferred in other recent studies of the Late Cenozoic evolution of this region (e.g., Partridge, 1997, 1998).

Fig. 14



The modelling results presented in Figure 14 thus envisage an increase in uplift rates in the Late Pliocene, followed by a relative lull in the Early Pleistocene, then a renewed increase in the Middle Pleistocene, when the Sundays River switched from aggrading across a broad region to a relatively narrow gorge, represented by terrace T4 onwards (Hattingh and Rust, 1999; Fig. 13b). This similarity suggests that the Sundays terraces have probably formed in the same way as those in Northern Hemisphere systems, in response to climatic forcing.

The main difference between these African records and river terrace staircases in Europe concerns the relative magnitudes of the Late Pliocene and Middle Pleistocene uplift phases. The present-day climate of most of the Sundays catchment is arid, with mean annual rainfall no more than ~300 mm (e.g., Schulze, 1972). Since there has been no Pleistocene glaciation in southern Africa, the most likely forcing agents for Middle Pleistocene uplift (by way of lower crustal flow) are erosion and cyclic loading of the continental crust beneath the offshore continental shelf in response to global sea-level fluctuations (Westaway, 2002a). The magnitude of this effect is evidently a consequence of high mobility of the lower crust in this region, due to its high heat flow. The even greater uplift rates deduced for the Late Pliocene thus require an additional cause: probably enhanced erosion. High rates of Late Pliocene erosion can be envisaged in this region, arising from the much wetter climatic regime known to have prevailed at that time (e.g., Tankard and Rogers, 1978; Tankard et al., 1982; Tyson, 1986).

3.5 Australia

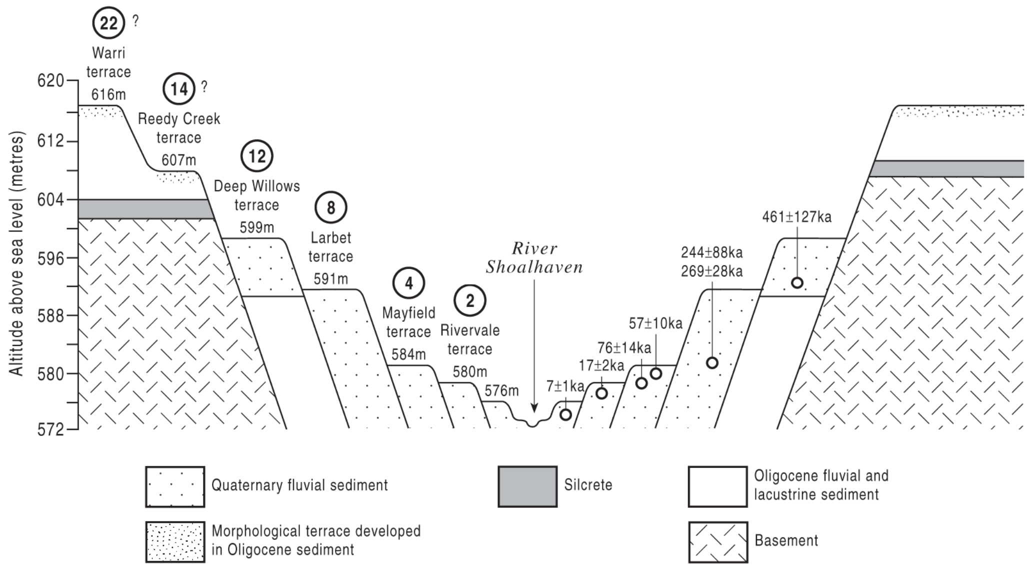
Australia is well known as a stable and ancient landscape, an axiom consistent with the occurrence there of significant cratonic provinces; much of Western Australia coincides with the Archaean Yilgarn and Pilbara cratons, identified as further examples of stable areas lacking Late Cenozoic terrace staircases by Westaway et al. (2003). The extreme stability of Australian Archaean crust is underpinned by estimates of Cretaceous sea-level and corresponding shorelines, which indicate net vertical motions since the Cretaceous of a few tens of metres at most (cf. Beard, 1998; Westaway et al., 2003).

Relative inactivity in other parts of this southern continent can perhaps be ascribed to increasing aridity - well documented in the internally draining Lake Eyre Basin (e.g., Kershaw and Nanson, 1993; Nanson and Price, 1998). The largest fluvial system in Australia, the Murray-Darling, can be shown to have existed since at least the Eocene and for much of its history fed into a subsiding depocentre, in which several hundreds of metres of fluvial, lacustrine and marine sediments accumulated (e.g., Brown and Radke, 1989; Stevenson and Brown, 1989). However, as in other parts of the world, uplift in the Late Cenozoic, estimated to be 60-110m since the beginning of the Middle Pleistocene (e.g., Huntley et al., 1993, 1994; Murray-Wallace et al., 1996) at a rate of between ~0.07 and ~0.13 mm a^{-1}, has led to incision into the earlier deposits and the formation of both fluvial and marine terraces. The uplift chronology is constrained by the dating of

Quaternary basalt of the Mount Gambier / Mount Schank volcanic field (cf Sheard, 1990), which caps Middle Pleistocene marine terrace deposits along the Southern Ocean coastline of eastern South Australia, ~300 km SSE of the mouth of the Murray. Uplift rates vary along this coastline, being lower in the vicinity of the mouth of the Murray and in the cratonic region farther west (e.g., Murray-Wallace, 2002).

A well-researched terrace record from ~900 km further ENE is that of the River Shoalhaven, which drains from the Great Dividing Range eastwards into the Tasman Sea to the south of Sydney (e.g., Nott, 1992; Nott et al., 2002; Fig. 15). According to Nott (1992), this river is ancient, having existed (like the Murray) throughout the Cenozoic. By the Oligocene it had established a broad valley, but in the Late Oligocene (~30 Ma) a basalt eruption dammed the river, creating a lake, ~80 km long, in which up to 60 m of sediment was deposited. The Shoalhaven has since incised into this Oligocene sediment by ~40 m, forming a staircase of six terraces, the youngest four of which have been dated by Nott et al. (2002) to MIS 12, 8, 4, and 2, using the TL technique (Fig. 15). Uplift modelling of this terrace staircase (not illustrated) suggests that the two oldest terraces may relate to MIS 22 and MIS 14 (Fig. 15), indicating typical uplift rates during the Middle-Late Pleistocene of ~0.05 mm a^{-1}. Simple extrapolation of the pattern of terrace heights in Figure 15 leads to the same conclusion.

Fig. 15



Comparative data are provided by the staircase of marine terraces on the adjacent coast of southern New South Wales. According to Young and Bryant (1993), there are Middle-Late

Pleistocene wave-cut platforms at 2 m (from MIS 5c or 5a), 4 m (MIS 5e), and 8 m a.s.l. (MIS 9 or older), all dated using amino acid, uranium series, or TL techniques, plus older undated platforms at 10 m a.s.l. (? Early Pleistocene) and ~20-30 m a.s.l. (? Miocene or older). Neglecting any effect of global eustatic sea-level fall, the uplift rate of this coastline was thus only ~0.002 mm a^{-1} during the Pliocene and Early Pleistocene (for ~10 m of uplift during ~6 to ~1 Ma) but ~0.01 mm a^{-1} since, again suggesting an increase in uplift rates in the early Middle Pleistocene, although the rates involved are lower here than elsewhere in the region.

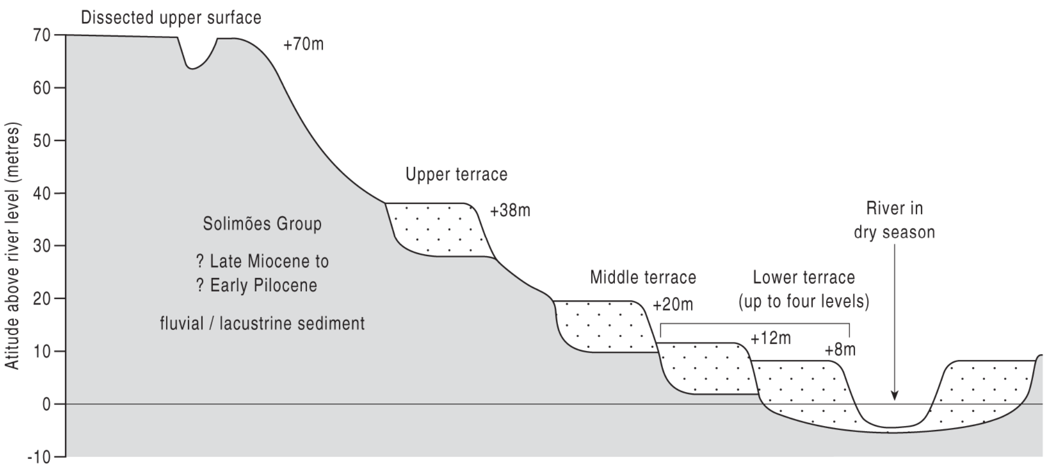
The evidence from the Shoalhaven (Fig. 15), which suggests terrace formation in approximate synchrony with Milankovitch cycles (like many rivers in the northern hemisphere), is thus consistent with the evidence from marine terraces in SE Australia. Both point to an increase in uplift rates in the late Early Pleistocene or early Middle Pleistocene, just as in many other regions of the world.

3.6 South America

Despite including the world's largest river system, the Amazon, relatively little is known of fluvial records in South America, with few reported terrace sequences. There have, however, been IGCP 449 contributions from Uruguay/Argentina (Parana-Uruguay system – Ubilla, 2004) and from Amazonia (Latrubesse and Rancy, 2000; Latrubesse, 2002; Westaway, 2006a). Much of Amazonia is on the Archaean crust of the Amazon Craton, which, given the observations noted above (cf. Westaway et al., 2003), might well explain the paucity of reported river terraces. Closer examination of the known geomorphology of this largely inaccessible region shows that terraces have indeed been recorded from patches of younger crust around the Amazon craton, although they are generally poorly researched. For example, around Rio Branco, western Brazil, west of the Amazon Craton (location of an IGCP 449 field meeting in June 2003), terraces occur at up to 70m above the present level of Amazon tributaries such as the Acre and Purus (Latrubesse et al., 1997; Westaway, 2006a; Fig. 16). These terraces are inset into an older stacked fluvial/lacustrine succession (the Solimões Group), deposition of which ended ~3 Ma (from biostratigraphy and Ar-Ar dating of interbedded tuff: cf. Westaway, 2006a). Terraces have also been documented from other tributaries of the Amazon, including the Jurua, Las Piedras and Madre de Dios, in both western Brazil and adjacent parts of Peru (~7-13° S; e.g., Räsänen et al., 1992; Latrubesse et al., 1997; Westaway, 2006a).

Further south, the River Mendoza, one of the most northerly tributaries of the Colorado system in central-western Argentina, has a staircase of at least six terraces (Brunotte, 1983). In a region of the Eastern Cordillera of the Andes that has witnessed cold-stage glacial advances (e.g., Espizua, 2000), these terraces relate to sedimentary complexes comprising pediments that pass downslope into fluvial or fluvioglacial aggradations. Brunotte (1983) noted that the oldest of these pediments is inset into a stacked sequence of fluvial conglomerate, the Mogotes Formation, of inferred Pliocene age, and that the top of this (at ~2500 m a.s.l.) is ~1200 m above present river level.

Fig. 16



Another Colorado tributary, the Diamante, ~150 km further south (around 34° 30' S), has a staircase of five terraces (Grosso and Corte, 1989). The highest of these is up to ~200 m above the river, over a zone many kilometres wide, inset into which are younger, much narrower terraces. On the basis of regional correlations, these five terraces (in reversed stratigraphical order) have been dated (Grosso and Corte, 1989) to the Late Würm (i.e., MIS 2), Early Würm (~MIS 4), 'Late Pleistocene' (possibly MIS 6), 'Middle Pleistocene' (~ MIS 12), and Early Pleistocene (~1.2-1.0 Ma). The attribution of terrace 2 to MIS 12 is based on the presence in sediments at a corresponding position in an adjacent river of deposits from an Andean pyroclastic flow dated to ~450 ky ago (Stern et al., 1984). According to Baker and Gosse (2003), rates of incision in this reach of the Diamante during the Middle and Late Pleistocene, based on this and other dating constraints, were typically ~0.2 mm a^{-1}, consistent with an age of ~1 Ma for the ~200 m fluvial terrace. These observations suggest that a broad river valley existed here in the Early Pleistocene but became progressively entrenched in the Middle-Late Pleistocene, exactly as is recorded in many European systems (see above).

Work in progress to date the incision history of the Diamante using cosmogenic isotopes (cf. Gosse et al., 2005) will enable this hypothesis to be tested.

Better documented are the terraces of the River Neuquen, a major affluent of the Negro, in central-southern Argentina. Garleff et al. (1983) have described four Neuquen terraces at up to 100m above river level. There is no age control, although Garleff et al. suggested that the lowest two terraces represented the last two glacials. The imprecision of the age interpretations from all these South American studies, together with the absence of any direct evidence for warm-stage activity, makes it impossible to establish whether climatic forcing has taken place, let alone explore its style. Nonetheless, this southern part of the continent has experienced similar climatic fluctuations to the areas in Europe in which the classic sequences of river terraces have formed, so it is tempting to suggest that a comparable mechanism of terrace generation has been active here.

4. Discussion: climatic forcing of terrace formation

From the worldwide examination undertaken as part of IGCP 449, terrace staircases are seen as ubiquitous features in landscapes all over the planet, recording significant fluvial incision during the Late Cenozoic, especially during the Middle and Late Pleistocene. The case studies reviewed above represent selected fluvial records from around the world, which, thanks especially to the work of project contributors, allow a level of international comparison hitherto impossible. A key comparative feature is uplift, which can be estimated from river terrace sequences and shows both remarkable similarities between regions as well as notable contrasts between different crustal types. There is reason to suggest that climate and uplift are coupled through mechanisms such as the isostatic response to changes in rates of erosion (cf. Westaway, 2001, 2002a). An important aspect of this is the apparently worldwide increase in uplift rates following the ‘Mid-Pleistocene Revolution’, seemingly a response to the start of 100 ky Milankovitch forcing. Furthermore, longer-timescale sequences such as those from the Rhine (Fig. 1), Maas (van den Berg, 1994; van den Berg and van Hoof, 2001), Dniester (Fig. 2) and Colorado (Fig. 11) show increases in uplift rates around 3 Ma; i.e. coincident with the climatic deterioration following the Middle Pliocene optimum (Westaway, 2002b). Where terrace levels can be dated, the vertical separation from the modern valley floor indicates time-averaged incision rates since ~1 Ma that vary between ~0.03 mm a^{-1} (e.g. the

Susquehanna; Westaway, in press) and ~0.2 mm a^{-1} (e.g., the Rhine; Figs 1 and 8f). Evidence from the best-dated long sequences, such as that from the Dniester (Fig. 2b), allow this incision record to be further resolved and interpreted as a measure of the pace of the surface uplift that has driven the downcutting. As already noted, however, this pattern is recognized only on post-Archaean crust; records from more ancient, cratonic areas, such as the Indian subcontinent and the Kaapvaal Craton in South Africa, show little net uplift during the Late Cenozoic (Fig. 3). This has led to the conclusion that only continental crust consolidated in the last ~2500 Ma retains the hot, mobile lower layer in which such vertical movement is generated (see above; Westaway et al., 2003).

An important additional observation that can now be made is that intermediate situations exist, in which fluvial records show fluctuating uplift and subsidence of long periodicity, with limited net change in level. These appear to be characteristic of Early Proterozoic crust, such as that forming the Ukrainian Shield, as indicated by the Dnieper and Don records (see above; Fig. 2c, d); such crust retains only a thin mobile lower layer and so is indeed intermediate between Archaean cratons and crust younger than the Middle Proterozoic. To a lesser extent the record from the Colorado (Fig. 11), again characterized by fluctuating uplift and subsidence of long periodicity, is a further example of this effect.

The thickness of the mobile lower crust can be characterized by the parameter W_i, defined in the caption of Figure 8. The modelling of the Colorado data in Figure 12 requires W_i=6 km, significantly less than the various examples from younger crustal provinces in Figure 8; similar modelling for the Dnieper and Don, not illustrated, requires W_i=5 km. The principal cause of the thinness of the mobile lower crustal layer in both these Early Proterozoic examples appears to be the presence of a thick layer of mafic material (which will not flow at the ambient temperatures and thus restricts the depth range of the overlying mobile layer), underplated at the base of the crust. In the case of the Colorado Plateau, which consolidated in the Early Proterozoic, the layer of mafic underplating was apparently emplaced at that time (e.g., Wendlandt et al., 1993). The age of the mafic underplating beneath the Ukrainian Shield is much less clear; some or all of it may represent the cumulative effect of subsequent mantle plume magmatism, such as that associated with the Devonian rifting in the Dnieper Basin (e.g., Chekunov et al., 1992; Wilson and Lyashkevich, 1996). Thick layers of mafic underplating, up to ~20 km, are commonly identified at the base of Early to Middle Proterozoic crust from seismic wave velocities (e.g., Durrheim and Mooney, 1991, 1994), which is thus often ~40-50 km thick. A thin mobile lower-crustal layer may thus be characteristic of such regions, leading to complex patterns of vertical crustal motion such as those observed in the Ukrainian Shield (Fig. 2c and d) and the Colorado Plateau (Fig. 11).

The idea that crustal rheology, inherited from the ancient geological past, affects rates of present-day vertical crustal motion is not new; it also underpins the work of others, such as the 'lithospheric memory' hypothesis of Cloetingh et al. (2005). However, as noted above, the observed vertical motions are here explained as consequences of coupling between surface processes and induced lower crustal flow, rather than being consequences of plate boundary forces, as Cloetingh et al. (2005) believed. The fluvial database reviewed here shows several examples of areas that are clearly unaffected by convergent plate motions, as required by the Cloetingh et al. hypothesis, and yet have river terrace sequences that record surface uplift. Examples are the Shoalhaven in Australia (Fig. 15), the Sundays in South Africa (Fig. 13) and the Colorado in the western USA (Fig. 11), none of which is near a recent convergent boundary; indeed the Colorado adjoins the actively extending Basin and Range Province.

4.1. Climatic forcing of terrace formation

The discussion will now explore the usefulness of the new (IGCP 449) data resource for examining the role of climatic fluctuation in river terrace formation. Uplift alone could perhaps have brought about terrace formation, particularly if it had taken the form of sporadic bursts of vertical movement interspersed with periods of stability (cf. Matoshko et al., 2004). Terraces that can be attributed to individual earthquake events are only to be found in plate boundary zones, however, where faults have very high slip rates (e.g. Leland et al., 1998). The minimal role of fault movement in accommodating lateral variations in uplift generated by lower crustal flow has been discussed elsewhere (Westaway, 2006b). Examples are known where slip on intraplate active faults is superimposed onto regional uplift, but this results in minor warping of terraces rather than the formation of additional features (e.g. Krzyszkowski et al., 2000; Westaway et al., 2006a).

Even without climatic triggering or sporadic uplift pulses, channel diversion as a result of avulsion, meander cut-off or capture could have resulted in terrace formation in areas of progressive elevation. Indeed, the weakly separated terraces of the Pravara and Kukadi systems of the Deccan plateau, India (Fig. 3a, b), appear to have resulted from shifts in the fluvial courses rather than progressive incision/aggradation cycles (cf. Westaway et al., 2003).

Shifting channels are always necessary, of course, for terraces to form; in uplifting regions, if channels remain fixed (e.g. in areas of highly resistant bedrock) the result is a deeply incised narrow valley or gorge, with minimal terrace preservation (as in Fig. 1b). Terraces formed by shifting channels will be localized, however, rather than traceable over large parts of catchments, as in the example terrace sequences used to illustrate this paper.

The most important support for climatic forcing of terrace formation comes from empirical evidence in those sequences in which palaeoclimatic indications are well preserved. This normally means fossils, although sedimentological and pedogenic (including cryogenic) evidence is of considerable importance in some instances. The evidence often indicates a climatic periodicity closely matching the cyclicity of the terraces. Examples of this are the cold-warm-cold sequences of the lower Thames (above; Fig. 4) and the consistent occurrence of interglacial beds capping the terraces of the Somme (Fig. 5). In systems for which a relationship with climatic fluctuation cannot be demonstrated, this is generally because evidence for variable palaeoclimate is rare or absent. In the absence of fossils or pedogenesis, the warm parts of climatic cycles will be difficult to demonstrate, even if they are represented within the sedimentary sequence. Clear records of interglacial climate frequently coincide with limestone bedrock and consequent calcareous ground water, which enable preservation of vertebrate and molluscan fossils and can even lead to travertine precipitation during climatic optima, as in the Wipper and other rivers of central Germany (Mania, 1995) and those of northern France (Antoine and Limondin-Lozouet, 2004; Antoine et al., in press). In regions where such evidence exists, it seems reasonable to use the records from areas of optimal preservation as analogies. In this way the spacing of terraces and their relation to less frequent dating points, such as glaciations or even the well-documented narrowing of valleys following the 'Mid-Pleistocene Revolution' (see above), can be used to compare with sequences elsewhere. Invariably the sequences with the best palaeoclimatic evidence will also be the best dated, on the basis of biostratigraphy, the various dating methods that use fossils as raw material or even from basic climato-stratigraphy. Exceptions to this occur in volcanic areas, where lavas and ash deposits interbedded with fluvial sequences can be dated by radiometric means (e.g. Pastre, 2004; Westaway et al., 2005, 2006b; Maddy et al., 2005). In addition, there is an increasing number of systems in which OSL dating has been applied to fluvial sands (e.g. Jain et al., 1999, 2004; Jain and Tandon, 2002; Briant et al., 2006) and ESR dating of fluvially transported quartz grains has been successfully employed in France (Antoine et al., 2003, in press; Despriée et al., 2004; Antoine and Limondin-Lozouet, 2004).

As noted, the idea that river terraces have been climatically generated is long established (Zeuner, 1945; Bourdier, 1968), although it fell out of favour during times when terrestrial sequences were viewed in terms of over-simplified climato-stratigraphical models (e.g. attempts to explain the post-Anglian Thames sequence in terms of only two climatic cycles – cf. Bridgland, 1994; Gibbard, 1994). With the recognition of nine 100 ky cycles since the 'Mid-Pleistocene Revolution', the potential for matching river terraces to climatic forcing is considerable. Detailed studies of fluvial activity during the last climatic cycle have revealed the importance of climate as a forcing factor (e.g, Macklin et al., 2002; Howard et al., 2004), despite such records being variably compromised by anthropogenic influences. It is therefore clear that cyclic changes in climate would be capable of driving terrace formation, given background uplift. This leaves more sophisticated questions to be explored, such as which are the most important parts of climatic cycles in terms of fluvial activity, whether all rivers respond in the same way, whether (as has always seemed likely) there are differences between climatic zones and whether humidity/precipitation, rather than temperature, can be the key factor in some cases.

It has already been noted that some rivers have cut down, forming new terraces, at cold-to-warm transitions, whereas others seem to have deepened their valleys following interglacials. It has also been noted that, whereas sequences exist with an approximate one-to-one match between terraces and glacial-interglacial (Milankovitch 100ky) cycles, there are many others with fewer terraces than this. A ready explanation exists for these records; the rivers have presumably responded only to the more significant climatic cycles, perhaps those identified by Kukla (2005) as supercycles. A good example is Kukla's (1975, 1977) own record from the River Svratka, Czech Republic. Rivers with more terraces than 100 ky cycles are rarer. The Somme (Fig. 5) has just one extra terrace, formed during MIS 7(b) (Antoine, 1994; Antoine et al., 2000), as does the Yonne, a Seine tributary (Chaussé et al., 2004). Another example is the Maas, for which an additional terrace has been attributed to MIS 13(b) (Westaway, 2002b). The Solent, mentioned above, has several extra terraces, perhaps achieving nearly two per 100 ky cycle during the late Middle Pleistocene (Westaway et al., 2006a). These examples are all from uplifting crustal areas in proximity to the Atlantic, the latter factor perhaps bringing the climatic sensitivity that has led to this type of extreme response.

4.2 Differences between climatic zones

The differing patterns of terrace preservation from the four eastern European rivers discussed above (Fig. 2), located within the temperate climatic zone, are important for showing that crustal type, rather than climate, is the key factor influencing the disposition of fluvial sedimentary archives. This is especially true since the cited examples of cratonic stability, namely in India, southern Africa and western Australia (Westaway et al., 2003; Fig. 3), are in warmer regions. There are several uncertainties involved in extrapolating explanations of terrace formation from cooler temperate regions to warmer climatic zones. These relate to the potential role, in the climatic forcing of fluvial activity, of permafrost (or more especially, its melting) and to whether fluctuations of temperature or precipitation are the most influential or whether other processes restricted to warmer climates might also be important. Indeed, following Büdel (1977, 1982), a view emerged that river terraces have not formed in the tropics, perhaps because these areas have not experienced the cold/periglacial – warm/interglacial fluctuations. The emphasis on such fluctuations in many explanations of terrace formation (Tyráček, 1983; Bridgland, 1994, 2000; Wymer, 1999) would seem to support Büdel's view. Data from IGCP 449 and earlier studies, however, have shown that terrace sequences are indeed present between the tropics, important examples occurring in the systems of the River Tana in Kenya (latitudes ~0-2° S; Veldkamp et al., 2004; in press), the River Niger in eastern Mali and southern Niger (~12-16° N; e.g., Beaudet et al., 1981; Dubois et al., 1984; Oussini and Morel, 1989; Bergoeing and Gilliard, 1997) and the various South America examples mentioned above. Büdel may have been misled, in formulating his views, by basing his impressions of tropical landscapes predominantly on his observations of cratonic areas such as Amazonia and the Archaean Congo Craton of central Africa, where the absence of terraces can now be seen to be the result of crustal stability rather than climatic regime.

The role of temperature as the control on Late Cenozoic fluvial activity may seem counter-intuitive, given the importance of precipitation, through its effect on discharge, in riverine processes. The importance of temperature, however, is first its influence on vegetation cover, which dictates the level of slope stability and thus bedload supply, and second its role in the periodic growth and decay of permafrost. In both respects this influence might be expected to decline with decreasing latitude, with lessening of the severity of the cold parts of climate cycles. However, there are indications that temperature is a controlling factor in areas well beyond the reach of the Quaternary glaciations; it has, for example, been invoked as significant in the Mediterranean region (Macklin et al., 2002; Martrat et al., 2004). The relation between the interglacial marine terraces of NW Syria and the fluvial terraces of the Kebir has already been noted (above) as evidence that the latter formed during cold stages, which implies that temperature can be the dominant influence as far south as the Mediterranean regions. A further important question is whether global temperature and humidity fluctuations during the Quaternary have been in phase (cf. Nanson et al., 1992); if temperature and humidity have been covariant during the last climatic cycle in Europe, their individual effects will be difficult to isolate.

It is generally believed that Quaternary temperature fluctuations have been considerably less severe in lower latitudes, although Milankovitch-driven fluctuations in humidity provide an alternative triggering system in such areas. Examples of terrace sequences in tropical regions for which aridity/humidity cycles are envisaged as principal forcing factors include the Amazon, in Brazil (Latrubesse et al., 1997), and the Niger, in the Niger Republic (e.g. Dubois et al., 1984; Oussini and Morel, 1989). Some systems in temperate regions might also be more susceptible to fluctuations of humidity, with its effect on discharge and vegetation density, than of temperature. Indeed, this type of forcing has been invoked for the eastern Mediterranean, where it has been linked to fluctuations in the strength of the Indian Ocean monsoon (e.g., Rossignol-Strick, 1985, 1999; Kroon et al., 1998). Similarly, aridity/humidity cycles are believed to be of considerable importance in Australia, set against a background of increasing aridity since the mid-Pleistocene (cf. Nanson et al., 1992, 1995, 1998).

5. Conclusions

The IGCP data confirm that aggradational river terraces, which dominate the long-timescale Quaternary fluvial record worldwide, result from the combined effects of progressive surface uplift and the cyclic climatic triggering of fluvial activity. Vertical disposition patterns vary according to crustal province rather than climatic zone, despite the importance of climatic factors and their influence, via vegetation, on landscape stability and, therefore, sediment supply. Previous received wisdom that terraces have not formed in the tropics is wrong; they occur wherever there is relatively young uplifting crust, although the climatic triggering may differ in contrasting climatic zones and may be stronger in some than in others. Another important difference between terrace records is in the numbers of terraces per climate cycle. Mid-late Quaternary systems with more than, less than and approximately one terrace per 100 ky cycle can all be observed. Where there are fewer terraces than cycles, it is likely that only the major events are represented; where there are more it is uncertain whether forcing is related to MIS subcycles or to both cooling-limb and warming-limb forcing. In sequences with just one terrace per 100 ky cycle, the varying stratigraphical position of interglacial sediments within individual terrace 'treads' suggests that examples exist of both warming- and cooling-limb forcing of incision. Despite the importance of precipitation in controlling fluvial processes, it would seem that temperature fluctuations are the key forcing factor, with the role of varying humidity yet to be demonstrated.

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References

Alekseev, M.N., Drouchits, V.A., 2004. Quaternary fluvial sediments; structure, distribution and genetic conditions in the Russian Arctic and Subarctic. Proceedings of the Geologists' Association 115, 339-346.

Antoine, P., 1994. The Somme Valley terrace system (northern France); a model of river response to Quaternary climatic variations since 800 000 BP. Terra Nova 6, 453-464.

Antoine P, Limondin-Lozouet N. 2004. Identification of MIS 11 Interglacial tufa deposit in the Somme valley (France): new results from the Saint-Acheul fluvial sequence. Quaternaire 15, 41-52.

Antoine, P., Lautridou, J.P., Laurent, M. 2000. Long-term fluvial archives in NW France: response of the Seine and Somme rivers to tectonic movements, climate variations and sea-level changes. Geomorphology 33, 183-207.

Antoine, P., Auguste, P., Bahain, J.J., Coudret, P., Depaepe, P., Fagnart, J.P., Falgueres, C., Fontugne, M., Frechen, M., Hatté, C., Lamotte, M., Laurent, M., Limondin-Lozouet, N., Locht, J.L., Mercier, N., Moigne, A.M., Munaut, A.V., Ponel, P., Rousseau, D.D. 2003. Paléoenvironnements pléistocènes et peuplements paléolithiques dans le bassin de la Somme (Nord de la France). Bulletin de la Société préhistorique Française 100, 5-28.

Antoine, P., Limondin-Lozouet, N., Chaussé, C., Lautridou, J.-P., Pastre, J.-F., Auguste, P., Bahain, J.J., Falguères, C., Galehb, B., in press. Pleistocene fluvial terraces from northern France (Seine, Yonne, Somme): synthesis and new results. Quaternary Science Reviews.

Arger, J., Mitchell, J., Westaway, R., 2000. Neogene and Quaternary volcanism of southeastern Turkey, In: Bozkurt, E., Winchester, J.A., Piper, J.D.A. (Eds.), Tectonics and Magmatism of Turkey and the Surrounding Area: Geological Society, London, Special Publication 173, pp. 459-487.

Baker, F., Rundell, J., Hasebi, K., Cole, R., Aslan, A., 2002. Geomorphic evolution of Grand Mesa, western Colorado. Geological Society of America, 2002 annual meeting, Abstracts with Programs, 34 (6), 472 (abstract).

Baker, S.E., Gosse, J.C., 2003. Quaternary bedrock incision history of the Rio Diamante, Mendoza Province, Argentina. Geological Society of America, 2003 annual meeting Abstracts with Programs 35 (6), 63.

Bar-Yosef, O., 1998. Early colonizations and cultural continuities in the Lower Palaeolithic of western Asia. In: Petraglia, M.D., Korisettar, R. (Eds.), Early Human Behaviour in Global Context. Routledge, London, pp. 221-279.

Beard, J.S., 1998. Position and developmental history of the central watershed of the Western Shield, Western Australia. Journal of the Royal Society of Western Australia 81, 157–164.

Beaudet, G., Coque, R., Michel, P., Rognon, P., 1981. Reliefs cuirassés et évolution géomorphlogique des régions orientales du Mali. 1. La région du Tilemsi et la vallée du Niger de Taoussa à Gao. Zeitschrift für Geomorphologie, N.F., Supplement 38, 38-62.

Bergoeing, J.P., Gilliard, P., 1997. Géomorphologie des terrasses du Fleuve Niger à la latitude du Parc National du W, Niger. Zeitschrift für Geomorphologie, N.F. 41, 491-504.

Besançon, J., Sanlaville, P., 1984. Terrasses fluviatiles au Proche-Orient. Bulletin de l'Association Française pour l'Étude du Quaternaire 21, 186-191.

Besançon, J., Sanlaville, P., 1993. La vallée de l'Oronte entre Rastane et Aacharné. In: Sanlaville, P., Besançon, J., Copeland, L., Muhesen, S. (Eds.), Le Paléolithique de la vallée moyenne de l'Oronte (Syrie): Peuplement et environnement. British Archaeological Review, International Series 587, 13-39.

Besançon, J., Copeland, L., Hours, F., Sanlaville, P., 1978. The Palaeolithic sequence in Quaternary formations of the Orontes river valley, northern Syria: a preliminary report. Bulletin of the Institute of Archaeology, London 15 149-170.

Bibus, E., Semmel, A., 1977. Über die Auswirkung quartärer Tektonik auf die altpleistozänen Mittelrhein Terrassen. Catena 4, 385-408.

Blum, M.D., Guccione, M.J., Wysocki, D., Robnett, P.C., 2000. Late Pleistocene evolution of the southern Mississippi Valley, southern Missouri to Arkansas. Geological Society of America Bulletin 112, 221-235.

Blum, M.D., Straffin, E.C., 2001. Fluvial responses to external forcing: examples from the French Massif Central, the Texas Coastal Plain (USA), the Sahara of Tunisia, and the lower Mississippi Valley (USA). In: Maddy, D., Macklin, M., Woodward, J. (Eds.), River Basin Sediment Systems: Archives of Environmental Change. Balkema, Rotterdam, pp. 195-228.

Bourdier, F., 1968. Les caractéristiques pédologiques des glaciations quaternaires de la Bièvre-Valloire. Excursions Sous-Commission INQUA pour la stratigraphie du Quaternaire européen, 9-10 May 1968. 12 pp.

Bourdier, F. (Ed.), 1974. Quaternaire et Paléolithique des Bassins de la Somme et de la Base-Seine. Bulletin de l'Association Française pour l'étude du Quaternaire 40-41, 273pp.

Braga, J.C., Martín, J.M., Quesada, C., 2003. Patterns and average rates of Late Neogene – Recent uplift of the Betic Cordillera, SE Spain. Geomorphology 50, 3-26.

Briant, R.M., Bates, M.R., Schwenninger, J-L., Wenban-Smith, F. 2006. An optically stimulated luminescence dated Middle to Late Pleistocene fluvial sequence from the western Solent Basin, southern England. Journal of Quaternary Science 21, 507–523.

Bridgland, D.R. 1994. Quaternary of the Thames. Chapman & Hall, London, 441 pp.

Bridgland, D.R. 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation. Quaternary Science Reviews 19, 1293-1303.
Bridgland, D.R. 2001. The Pleistocene evolution and Palaeolithic occupation of the Solent River. In: Wenban-Smith, F.F., Hosfield, R.T. (Eds.) Palaeolithic archaeology of the Solent River. Lithic Studies Society Occasional Paper 7. Lithic Studies Society, London, pp. 15-25.
Bridgland, D.R., 2006. The Middle and Upper Pleistocene sequence in the Lower Thames: a record of Milankovitch climatic fluctuation and early human occupation of southern Britain. Proc. Geol. Assoc. 117, 281-305.
Bridgland, D.R., Schreve, D.C., 2001. River terrace formation in synchrony with long-term climatic fluctuation: supporting mammalian evidence from southern Britain. In: Maddy, D., Macklin, M., Woodward, J. (Eds.), River Basin Sediment Systems: Archives of Environmental Change. Balkema, Abingdon, England, p. 229-248.
Bridgland, D.R., Schreve, D.C. 2004. Quaternary lithostratigraphy and mammalian biostratigraphy of the Lower Thames terrace system, south-east England. Quaternaire 15, 29-40.
Bridgland, D.R., Philip, G., Westaway, R., White, M. 2003. A long Quaternary terrace sequence in the Orontes River valley, Syria: a record of uplift and of human occupation. Current Science (New Delhi) 84, 1080-1089.
Bridgland, D.R., Maddy, D., Bates, M. 2004a. River terrace sequences: templates for Quaternary geochronology and marine-terrestrial correlation. Journal of Quaternary Science 19, 203-218.
Bridgland, D.R., Schreve, D.C., Keen, D.H., Meyrick, R., Westaway, R., 2004b. Biostratigraphical correlation between the late Quaternary sequence of the Lower Thames and key fluvial localities in central Germany. Proceedings of the Geologists' Association 115, 125-140.
Bridgland, D.R., Antoine, P., Limondin-Lozouet, N., Santisteban, J.I., Westaway, R., White, M.J., 2006. The Palaeolithic occupation of Europe as revealed by evidence from the rivers: data from IGCP 449. Journal of Quaternary Science 21, 437-455.
Brown, C.M., Radke, B.M., 1989. Stratigraphy and sedimentology of the Mid-Tertiary permeability barriers in the subsurface of the Murray Basin. BMR Journal of Australian Geology and Geophysics 11, 367-385.
Brunotte, E., 1983. Zur allochtonen Formung quartärer Fußflächen in Bolsonen W-Argentiniens. Zeitschrift für Geomorphologie, N.F., Supplement 48, 203-212.
Bryant, B., Kunk, M.J.; Kirkham, R.M., 2002. Timing and rates of late Cenozoic incision by the Colorado River in Glenwood Canyon, Colorado. Geological Society of America, 2002 annual meeting, Abstracts with Programs, 34 (6), 320-321 (abstract).
Büdel, J. 1977. Klima-Geomorphologie. Gebrüder Borntraeger, Berlin.
Büdel, J. 1982. Climatic Geomorphology. English translation by Fischer, L. Busche, D. Princeton University Press, Princeton, NJ, 443pp.
Bull, W.B., 1991. Geomorphic Responses to Climatic Change. Oxford University Press, Oxford, 326pp.
Bull, W.B., Kneupfer, P.L.K., 1987. Adjustments by the Charwell River, New Zealand, to uplift and climatic changes. Geomorphology 1, 15-32.
Bunbury, J.M., Hall, L., Anderson, G.J., Stannard, A., 2001. The determination of fault movement history from the interaction of local drainage with volcanic episodes. Geological Magazine 138, 185-192.
Butzer, K., Helgren, D., Fock, G., Stuckenrath, R., 1973. Alluvial terraces of the lower Vaal River, South Africa: A reappraisal and reinvestigation. Journal of Geology 81, 341-362.

Chaussé, C., Voinchet, P., Bahain, J.-J., Connet, N., Lhomme, V., Limondin-Lozouet, N., 2004. Middle and upper Pleistocene evolution of the River Yonne valley (France); first results. Quaternaire 15, 53-64.
Chekunov, A.V., Garvish, V.K., Kutas, R.I., Ryabchun, L.I., 1992. Dnieper-Donets paleorift. Tectonophysics 208, 257-272.
Clet-Pellerin, M., Occhietti, S., 2000. Pleistocene palynostratigraphy in the St. Lawrence Valley and middle estuary. Quaternary International 68-71, 39-57.
Cloetingh, S.A.P.L., Ziegler, P.A., Beekman, F., Andriessen, P.A.M., Matenco, L., Bada, G., Garcia-Castellanos, D., Hardebol, N., Dezes, P., Sokoutis, D., 2005. Lithospheric memory, state of stress and rheology: neotectonic controls on Europe's intraplate continental topography. Quaternary Science Reviews 24, 241-304.
Copeland, L., Hours, F., 1993. The Middle Orontes paleolithic flint industries. In: Sanlaville, P., Besançon, J., Copeland, L., Muhesen, S. (Eds.), Le Paléolithique de la vallée moyenne de l'Oronte (Syrie): Peuplement et environnement. British Archaeological Review, International Series 587, 63-144.
Cordier, S., Harmand, D., Losson, B., Beiner, M. 2004. Alluviation of the Meurthe and Moselle valleys (Eastern Paris Basin, France): lithological contribution to the study of the Moselle capture and Pleistocene climatic fluctuations. Quaternaire 15, 65-76.
Cordier, S., Harmand, D., Frechen, M., Beiner, M. 2006. Fluvial system response to Middle and Upper Pleistocene climate change in the Meurthe and Moselle valleys (Eastern Paris Basin and Rhenish Massif). Quaternary Science Reviews 25, 1460-1474.
Damon, P.E., Shafiqullah, M., Leventhal, J.S., 1974. K-Ar chronology for the San Francisco volcanic field and rate of erosion of the Little Colorado River. In: Karlstrom, T.N.V., Swann, G.A., Eastwood, R.L. (Eds.), Geology of Northern Arizona with Notes on Archeology and Paleoclimate: Part 1, Regional Studies. Geological Society of America, Rocky Mountain Section, 27th Annual Meeting, Flagstaff, Arizona, pp. 221-235.
De Mets, C., Gordon, R.G., Argus, D.F., Stein, S., 1994. Effect of recent revision to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters 21, 2191-2194.
Demir, T., Yeşilnacar, İ, Westaway, R., 2004. River terrace sequences in Turkey: sources of evidence for lateral variations in regional uplift. Proceedings of the Geologists' Association 115, 289-311.
Despriée, J., Gageonnet, R., Voinchet, P., Bahain, J-J., Falguères, C., Duvialard, J., Varache, F. 2004. Pleistocene fluviatile systems of the Creuse river (Middle Loire basin - Centre region (France). Quaternaire 15, 77-86.
Dethier, D.P., Schildgen, T., Bierman, P., Caffee, M., 2001. Cosmogenic analysis of the Rocky Flats alluvium near Boulder, Colorado. Geological Society of America, 2001 annual meeting, Abstracts with Programs 33 (6), 312-313.
De Wit, M.C.J. 2004. The diamondiferous sediments on the farm Nooitgedacht (66), Kimberley, South Africa. South African Journal of Geology 107, 477-488.
De Wit, M.C.J., Ward, J.D., Jacob, J.R., 1997. Diamond-bearing deposits of the Vaal-Orange river system. Field Excursion Guidebook, 6th International Conference on Fluvial Sedimentology, University of Cape Town, September 1997, vol. 2, p. 1-61.
Dodonov, A.E., Deviatkin, E.V., Ranov, V.A., Khatib, K., Nseir, H., 1993. The Latamne Formation in the Orontes river valley. In: Sanlaville, P., Besançon, J., Copeland, L., Muhesen, S. (Eds.), Le Paléolithique de la vallée moyenne de l'Oronte (Syrie): Peuplement et environnement. British Archaeological Reports, International Series 587, 189-194.
Dingle, B.V., Hendey, Q.B., 1984. Mesozoic and Tertiary sediment supply to the western Cape Basin and palaeodrainage systems in south-western Africa. Marine Geology 56,

13-26.

Dubois, D., Icole, M., Trichet, J., 1984. Évolution géomorphologique de la vallée du Niger aux abords de Niamey (République du Niger). Bull. Soc. Géol. Fr., ser. 7, 26, 1305-1318.

Durrheim, R.J., Mooney, W.D., 1991. Archean and Proterozoic crustal evolution; evidence from crustal seismology, Geology 19, 606-609.

Durrheim, R.J., Mooney, W.D., 1994. Evolution of the Precambrian litrhosphere: seismological and geochemical constraints. J. Geophys. Res. 99, 15359-15374.

Espizua, L.E., 2000. Quaternary glacial sequence in the Río Mendoza valley, Argentina. In: Smolka, P., Volkheimer, W. (Eds.), Southern Hemisphere Paleo- and Neoclimates: Key Sites, Methods, Data and Models. Springer-Verlag, Berlin, pp. 287-293.

Fisk, H.N. 1951. Loess and Quaternary geology of the Lower Mississippi Valley. Journal of Geology 59, 333-356.

Gansecki, C.A., Mahood, G.A., McWilliams, M., 1998. New ages for climactic eruptions at Yellowstone: single-crystal ^{40}Ar/^{39}Ar dating identifies contamination. Geology 26, 343-346.

Garhart, A., Aslan, A., Betton, C.W., 2003. Origin of late Cenozoic lacustrine deposits on the Uncompahgre Plateau of western Colorado. Geological Society of America, 2003 annual meeting, Abstracts with Programs 35 (6), 170.

Garleff, K., Stingl, H., Lambert, K.-H., 1983. Flußflächen- und Terrassentreppen im Einzugsbereich des oberen Río Neuquén, Argentinien. Zeitschrift für Geomorphologie, N.F., Supplement 48, 247-259.

Garvin, C.D., Hanks, T.C., Finkel, R.C., Heimsath, A.M., 2005. Episodic incision of the Colorado River in Glen Canyon, Utah. Earth Surface Processes and Landforms 30, 973-984.

Gibbard, P.L., 1985. The Pleistocene history of the Middle Thames Valley. Cambridge University Press, Cambridge, 155pp.

Gibbard, P.L., 1994. Pleistocene History of the Lower Thames Valley. Cambridge University Press, Cambridge, 229 pp.

Gosse, J.C., Baker, S., Pazzaglia, F., Brandon, M.T., Karlstrom, K., Pederson, J., Finkel, R.C., 2005. Five ways to examine what isn't there with cosmogenic isotopes. Abstracts of the 15th annual V.M. Goldschmidt conference, Moscow, Idaho, May 2005. Geochimica et Cosmochimica Acta 69 (10), 163.

Grosso, S.A., Corte, A.E., 1989. Pleistocene ice wedge casts at 34° S, eastern Andes piedmont, south-west of South America. Geografiska Annaler A 71, 125-136.

Green, C.P., McGregor, D.F.W. 1980. Quaternary evolution of the River Thames. In: Jones, D.K.C. (Ed.), The Shaping of Southern England, Institute of British Geographers Special Publication 11, Academic Press, London, pp. 177 202.

Green, C.P., McGregor, D.F.W. 1987. River terraces: a stratigraphical record of environmental change. In: Gardiner, V. (Ed.), International Geomorphology 1986 Part 1., Wiley, Chichester, pp. 977-987.

Hanks, T.C., Blair, J.L., 2003. Differential incision of the Grand Canyon related to Quaternary faulting—Constraints from U-series and Ar/Ar dating: comment. Geology Online Forum, p. e16–e17 (published online; doi: 10.1130/0091-7613(2003)31<e16:DIOTGC>2.0.CO;2).

Hansen, W.R., 1987. The Black Canyon of the Gunnison - in depth. Southwest Parks and Monuments Association, Tucson, Arizona, 58 pp.

Harvey, A.M., Wells, S.G., 1987. Response of Quaternary fluvial systems to differential epeirogenic uplift: Aguas and Feos river systems, southeast Spain. Geology 15, 689-693.

Hattingh, J., 1994. Depositional environment of some gravel terraces in the Sundays River valley, Eastern Cap. South African Journal of Geology 97, 156-166.

Hattingh, J., Goedhart, M.L., 1997. Neotectonic control on drainage evolution in the Algoa Basin, southeastern Cape Province. South African Journal of Geology 100, 43-52.

Hattingh, J., Rust, I., 1999. Drainage evolution and morphological development of the late Cenozoic Sundays River, South Africa. In: Miller, A., Gupta, A. (Eds.), Varieties of Fluvial Form. International Association of Geomorphologists Geomorphology Publication 7, pp. 145-166.

Heller, P.L., Dueker, K., McMillan, M.E., 2003. Post-Paleozoic alluvial gravel transport as evidence of continental tilting in the U.S. Cordillera. Geological Society of America Bulletin 115, 1122-1132.

Helgren, D.M., 1977. Geological context of the Vaal River faunas. South African Journal of Science 73, 303-307.

Helgren, D.M., 1978. Acheulian settlement along the lower Vaal River, South Africa. Journal of Archaeological Science 5, 39-60.

Howard, A.J., Macklin, M.G., Bailey, D.W., Mills, S., Andreescu, R. 2004. Late-glacial and Holocene river development in the Teleorman Valley on the southern Romanian Plain. Journal of Quaternary Science 19, 271-280.

Huntley, D.J., Hutton, J.T., Prescott, J.R., 1993. The stranded beach-dune sequence of south-east South Australia: A test of thermoluminescence dating, 0-800 ka. Quaternary Science Reviews, 12, 1-20.

Huntley, D.J., Hutton, J.T., Prescott, J.R., 1994. Further thermoluminescence dates from the dune sequence in the south-east of South Australia. Quaternary Science Reviews 13, 201-207.

Jain, M., Tandon, S.K. 2003. Fluvial response to Quaternary climate change, western India, Quaternary Science Reviews 22, 2223-2235.

Jain, M., Tandon S.K., Bhatt, S.C., Singhvi, A.K., Mishra, S., 1999. Alluvial and aeolian sequences along the River Luni, Barmer District: physical stratigraphy and feasibility of luminescence chronology methods. Memoirs of the Geological Society of India 42, 273-295.

Jain, M., Murray, A.S., Bøtter-Jensen, L. 2004. Optically stimulated luminescence dating: How significant is incomplete light exposure in fluvial environments. Quaternaire 15, 143-157.

Karlstrom, K.E., 2005. Influences of Quaternary tectonism on the profile and incision history of the Colorado River system of the Southwestern U.S.. Geological Society of America, Rocky Mountain Section, 57th annual meeting, Abstracts with Programs, 37 (6), 15 (abstract).

Karner, D.B., Marra, F., 1998. Correlation of fluviodeltaic aggradational sections with glacial climate history: a revision of the Pleistocene stratigraphy of Rome. Geological Society of America Bulletin 110, 748-758.

Kellogg, K.S., 2004. The geologic story of the Gunnison Gorge National Copnservation Area, Colorado. U.S. Geological Survey Professional Paper 1699, 50 pp.

Kershaw, A.P., Nanson, G.C., 1993. The last full glacial cycle in the Australian region. Global and Planetary Change 7, 1-9.

Kiden, P., T.E. Törnqvist, 1998. Can river terrace flights be used to quantify Quaternary tectonic uplift rates? Journal of Quaternary Science 13, 573-574.

Kroon, D., Alexander, I., Little, M., Lourens, L.J., Matthewson, A., Robertson, A.H.F., Sakamoto, T., 1998. Oxygen isotope and sapropel stratigraphy in the Eastern Mediterranean during the last 3.2 million years. Proceedings of the Ocean Drilling Program, Scientific Results 160, 181-189.

Krzyszkowski, D. Przybylski, B, Badura, J. 2000. The role of neotectonics and glaciations along the Nysa-Klodzka River in the Sudeten Mountains (southwestern Poland). Geomorphology 33, 149-166.

Kukla, G.J., 1975. Loess stratigraphy of Central Europe. In: Butzer, K.W., Isaac, G.L. (Eds.), After the Australopithecines: Stratigraphy, Ecology and Culture Change in the Middle Pleistocene. Mouton, The Hague, pp. 99-188.

Kukla, G.J., 1977. Pleistocene land-sea correlations. I. Europe. Earth Science Reviews 13, 307-374.

Kukla, G.J., 1978. The classical European glacial stages: correlation with deep-sea sediments. Transactions of the Nebraska Academy of. Science 6, 57-93.

Kukla, G. 2005. Saalian supercycle, Mindel/Riss interglacial and Milankovitch's dating. Quaternary Science Reviews 24, 1573-1583.

Latrubesse, E.M. 2002. Evidence of Quaternary palaeohydrological changes in Middle Amazonia: the Aripuaña-Roosvelt and Jiparaná "fans". Zeitschrift fur Geomorphologie 129, 61-72.

Latrubesse, E.M., Rancy, A. 2000. Neotectonic influence on tropical rivers of southwestern Amazon during the late Quaternary: the Moa and Ipixuna river basins, Brazil. Quaternary International 72, 67-72.

Latrubesse, E., Bocquentin, J., Santos, J.C.R., Ramonell, 1997. Paleoenvironmental model for the Late Cenozoic of southwestern Amazonia: paleontology and geology. Acta Amazonica 27, 103-118.

Leland, J., Reid, M. R., Burbank, D.W., Finkel, R., Caffee, M., 1998. Incision and differential bedrock uplift along the Indus River near Nanga Parbat, Pakistan Himalaya, from ^{10}Be and ^{26}Al exposure age dating of bedrock straths, Earth and Planetary Science Letters 154, 93-107.

Le Roux, F.G., 1989. The lithostratigraphy of Cenozoic deposits along the south-east Cape coast as related to sea-level changes. MSc thesis, Stellenbosch University, South Africa, 247 pp.

Le Roux, F.G., 1990. Palaeontological correlation of Cenozoic marine deposits of the southeastern, southern and western coasts, Cape Province. South African Journal of Geology 93, 514-518.

Lindsey, D.A., Langer, W.H., Cummings, L.S., Shary, J.F., 1998. Gravel deposits of the South Platte River valley north of Denver, Colorado. Part A: Stratigraphy and sedimentary structures. U.S. Geological Survey Open-File Report 98-148-A, 22pp.

Lucchitta, I., Curtiss, G.H., Davis, M.E., Davis, S.W., Turrin, B., 2000. Cyclic aggradation and downcutting, fluvial response to volcanic activity, and calibration of soil-carbonate stages in the western Grand Canyon, Arizona. Quaternary Research 53, 23-33.

Macklin, M.G., Fuller, I.C., Lewin, J., Maas, G.S., Passmore, D.G., Rose, J., Woodward, J.C., Black, S., Hamlin, R.H.B., Rowan, J.S., 2002. Correlation of fluvial sequences in the Mediterranean basin over the last 200 ka and their relationship to climate change. Quaternary Science Reviews 21, 1633-1641.

Maddy, D., 1997. Uplift-driven valley incision and river terrace formation in southern England. Journal of Quaternary Science 12, 539-545.

Maddy, D., Bridgland, D.R., Green, C.P., 2000. Crustal uplift in southern England; evidence from the river terrace records. Geomorphology 33, 167-181.

Maddy, D., Keen, D.H., Bridgland, D.R., Green, C.P., 1991. A revised model for the Pleistocene development of the River Avon, Warwickshire. Journal of the Geological Society, London 148, 473-484.

Maddy, D., Demir, T., Bridgland, D.R., Veldkamp, A., Stemerdink, C., Van der Schriek, T., Westaway, R. 2005. An obliquity-controlled Early Pleistocene river terrace record from

weatern Turkey? Quaternary Research 63, 339-346.
Mania, D., 1995. The earliest occupation of Europe: the Elbe-Saala region (Germany). In: Roebroeks, W., Van Kolfschoten, T. (Eds.), The Earliest Occupation of Europe. University of Leiden, The Netherlands, pp 85-101.
Martrat, B., Grimalt, J.O., Lopez-Martinez, C., Cacho, I., Sierro, F.J., Flores, J.A., Zahn, R., Canals, M., Curtis, J.A., Hodell, D.A., 2004. Abrupt temperature changes in the western Mediterranean over the past 250,000 years. Science 306, 1762-1765.
Mather, A.E., Stokes, M., 2003. Long-term landscape development in southern Spain. Geomorphology 50, 1-2.
Matoshko, A.V., Gozhik, P.F., Ivchenko A.S. 2002 The fluvial archive of the Middle and Lower Dnieper (a review). Netherlands Journal of Geosciences 81, 339-355.
Matoshko, A., Gozhik, P., Danukalova, G., 2004. Key Late Cenozoic fluvial archives of eastern Europe: the Dniester, Dnieper, Don and Volga: Proceedings of the Geologists' Association 115, 141-173.
Maud, R.R., 1968. Quaternary geomorphology and soil formation in coastal Natal. Zeitschrift für Geomorphologie, N.F., Supplement 7, 155-199.
McCave, I.N., 1969. Correlation of marine and nonmarine strata with example from the Devonian of New York state. American Association of Petroleum Geologists Bulletin 53, 155-162.
McMillan, I.K., 1990. A foraminiferal biostratigraphy and chronostratigraphy for the Pliocene to Pleistocene Upper Algoa group, Eastern Cape, South Africa. South African Journal of Geology 93, 622-644.
McMillan, M.E., Angevine, C.L., Heller, P.L., 2002. Postdepositional tilt of the Miocene-Pliocene Ogallala Group on the western Great Plains: Evidence of Late Cenozoic uplift of the Rocky Mountains. Geology 30, 63-66.
Meyer, W., Stets, J., 1998. Junge Tektonik im Rheinischen Schiefergebirge und ihre Quantifizierung. Zeitschrift der Deutschen Geologischen Gesellschaft 149, 359-379.
Mishra, S., 1995. Prehistoric and Quaternary Studies at Nevasa: The Last Forty Years. Memoirs of the Geological Society of India 32, 324-332.
Mitchell, J., Westaway, R., 1999. Chronology of Neogene and Quaternary uplift and magmatism in the Caucasus: Constraints from K-Ar dating of volcanism in Armenia, Tectonophysics 304, 157-186.
Muhesen, S., 1993. L'Acheuléan recent évolué de l'Oronte. In: Sanlaville, P., Besançon, J., Copeland, L., Muhesen, S. (Eds.), Le Paléolithique de la vallée moyenne de l'Oronte (Syrie): Peuplement et environnement. British Archaeological Reports, International Series 587, 145-166.
Murray-Wallace, C.V. 2002. Pleistocene coastal stratigraphy, sea-level highstands and neotectonism of the southern Australian passive continental margin - a review. Journal of Quaternary Science 17, 469-489.
Murray-Wallace, C.V., Belperio, A.P., Cann, J.H., Huntley, D.J., Prescott, J.R., 1996. Late Quaternary uplift history, Mount Gambier region, South Australia. Zeitschrift für Geomorphologie, N.F., Supplement 106, 41-56.
Nanson, G.C., Price, D.M., 1998. Quaternary change in the Lake Eyre Basin of Australia; an introduction. Palaeogeography, Palaeoclimatology, Palaeoecology 144, 235-237.
Nanson, G.C., Price, D.M., Short, S.A. 1992. Wetting and drying of Australia over the past 300 ka. Geology 20, 791-794.
Nanson, G.C., Chen, X. Y., Price, D.M. 1995. Aeolian and fluvial evidence of changing climate and wind patterns during the past 100 ka in the western Simpson Desert, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 113, 87-102.
Nanson, G.C., Callen, R.A., Price, D.M. 1998. Hydroclimatic interpretation of Quaternary

shorelines on South Australian playas. Palaeogeography, Palaeoclimatology, Palaeoecology 144, 281-305.

Nikishin, A.M., Ziegler, P.A., Stephenson, R., Cloetingh, S., Furne, A.V., Fokin, P.A., Ershov, A.V., Bolotov, S.N., Korotaev, A.S., Alekseev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankreijer, A., Shalimov, I.V., 1996. Late Precambrian to Triassic history of the East-European Craton: Dynamics of Basin Evolution. Tectonophysics 268, 23-63.

Nikishin, A.M., Brunet, M.F., Cloetingh, S., Ershov, A.V., 1997. Northern peri-Tethyan Cenozoic intraplate deformations; influence of the Tethyan collision belt on the Eurasian continent from Paris to Tian-Shan. Comptes Rendus de l'Academie des Sciences, Paris, Series IIa 324, 49-57.

Nott, J.F., 1992. Long-term drainage evolution in the Shoalhaven catchment, southeast highlands, Australia. Earth Surface Processes and Landforms 17, 361-374.

Nott, J.F., Price, D., Nanson, G., 2002. Stream response to Quaternary climate change: evidence from the Shoalhaven River catchment, southeastern highlands, temperate Australia. Quaternary Science Reviews 21, 965-974.

Osterkamp, W.R., Fenton, M.M., Gustavson, T.C., Hadley, R.F., Holliday, V.T., Morrison, R.B., Toy, T.J., 1987. Great Plains. In: Graf, W.L. (Ed.), Geomorphic Systems of North America, Centennial Special Volume 2. Geological Society of America, Boulder, Colorado, pp. 163-210.

Ousseini, I., Morel. A., 1989. Utilisation de formations alluviales azoïques pour l'étude des paléoenvironnements du Pléistocène Supérieur et de l'Holocène au sud du Sahara: l'exemple de la vallée du Fleuve Niger dans le Liptako Nigérien. Bull. Soc. Géol. France, Series 8 5, 85-90.

Ozaner, F.S., 1992. Detecting the polycyclic drainage evolution in Kula region (western Turkey) using aerial photographs. ITC Journal [International Journal of Applied Earth Observation and Geoinformation] 1992-3, 249-253.

Partridge, T.C, 1997. Late Neogene uplift in eastern and southern Africa and its paleoclimatic implications. In: Ruddiman, W.F. (Ed.), Tectonic Uplift and Climate Change. Plenum Press, New York, pp. 63-86.

Partridge, T.C., 1998. Of diamonds, dinosaurs and diastrophism: 150 million years of landscape development in southern Africa. South African Journal of Geology 101, 167-184.

Pastre, J.F., 2004. The Perrier plateau; a Plio-Pleistocene long fluvial record in the River Allier basin, Massif central, France. Quaternaire 15, 87-101.

Patyk-Kara, N.G., Postolenko, G.A., 2004. Structure and evolution of the Kolyma river valley: from upper reaches to continental shelf. Proceedings of the Geologists' Association 115, 325-338.

Pazzaglia, F.J., Gardner, T.W., 1994. Late Cenozoic flexural deformation of the middle U.S. Atlantic passive margin. Journal of Geophysical Research 99, 12143-12157.

Pederson, J.L.K., Sharp, W.D., McIntosh, W., 2002. Differential incision of the Grand Canyon related to Quaternary faulting; constraints from U-series and Ar/Ar dating. Geology 30, 739-742.

Pederson, J., Karlstrom, K., Sharp, W., McIntosh, W., 2003. Differential incision of the Grand Canyon related to Quaternary faulting - Constraints from U-series and Ar/Ar dating: reply. Geology Online Forum, p. e17 (published online; doi: 10.1130/0091-7613(2003)31<e17:R>2.0.CO;2).

Räsänen, M., Neller, R., Salo, J., Jungner, H., 1992. Recent and ancient fluvial deposition systems in the Amazonian foreland basin, Peru. Geol. Mag. 129, 293-306.

Reed, E.C., Dreeszen, V.H., Bayne, C.K., Schultz, C.B., 1965. The Pleistocene in Nebraska and northern Kansas. In: Wright, Jr., H.E., Frey, D.G. (Eds.), The Quaternary of the

United States Princeton University Press, Princeton, New Jersey, pp. 187-202.
Rose, J., Allen, P. 1977. Middle Pleistocene stratigraphy in south east Suffolk. Journal of the Geological Society, London 133, 83-102.
Rossignol-Strick, M., 1985. Mediterranean Quaternary sapropels, an immediate response of the African monsoon to variations of insolation. Palaeogeography, Palaeoclimatology, Palaeoecology 49, 237-263.
Rossignol-Strick, M., 1999. The Holocene climatic optimum and pollen records of sapropel 1 in the eastern Mediterraneran, 9000-6000 BP. Quaternary Science Reviews 18, 515-530.
Said, R., 1981. The geological evolution of the River Nile. Springer-Verlag, New York, 151pp.
Saucier, R.T., 1996. Geomorphology and Quaternary geologic history of the Lower Mississippi Valley. U.S. Army Corps of Engineers, Vicksburg, Mississippi, 364pp.
Schildgen, T., Dethier, D.P., Bierman, P., Caffee, M., 2002. ^{26}Al and ^{10}Be dating of Late Pleistocene and Holocene fill terraces: a record of fluvial deposition and incision, Colorado Front Range. Earth Surface Processes and Landforms 27, 773-787.
Schreve, D.C., Bridgland, D.R., 2002. Correlation of English and German Middle Pleistocene fluvial sequences based on mammalian biostratigraphy. Netherlands Journal of Geoscience 81, 357-373.
Schulte, L., 2002. Quaternary Evolution of the Vera and eastern Sorbas Basin (SE Iberian Peninsula). A reconstruction of paleoclimatic fluctuations from morphological and pedological studies. University of Barcelona Press, Barcelona, Spain, 251 pp. ISBN 84-475-2669-0 (in Spanish with English summary).
Schulte, L., Gómez Ortiz, A., Passmore, D., 2000. Sobre los supuestos restos periglaciares Pleistocenos en los llanos del sureste de la Península Ibérica. In: Peña, M., Sánchez-Fabre, M., Lozano, M.V. (Eds.), Procesos y Formas Periglaciares en la Montaña Mediterránea. Instituto de Estudios Turolenses, Teruel, Spain, pp. 281-297.
Schulze, B.R., 1972. South Africa. In: Griffiths, J.F. (Ed.), Climates of Africa, World Survey of Climatology vol. 10. Elsevier, Amsterdam, pp. 501-586.
Scott, R.B., Steven, T.A., Betton, C.W., Cole, R.D., Aslan, A., Hood, W.C., 2002. Evidence for late Cenozoic uplift on the Uncompahgre Plateau, northeastern Colorado Plateau. Geological Society of America, 2002 annual meeting, Abstracts with Programs 34 (6), 322 (abstract).
Şengör, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature 364, 299-307.
Sheard, M.J., 1990. A guide to the Quaternary volcanoes in the lower south-east of South Australia. Mines and Energy Review, South Australia 157, 40-50.
Starkel, L., 2003. Climatically controlled terraces in uplifting mountain areas. Quaternary Science Reviews 22, 2189-2198.
Stevenson, A.E., Brown, C.M., 1989. The ancient Murray river system. BMR Journal of Australian Geology and Geophysics 11, 387-395.
Stern, C.R., Amini, H., Charrier, R., Godoy, E., Herve, A.F., Varela, J., 1984. Petrochemistry and age of rhyolitic pyroclastic flows which occur along the drainage valleys of the Rio Maipo and Rio Cachapoal (Chile) and the Rio Yaucha and Rio Papagayos (Argentina). Revista Geologica de Chile 23, 39-52.
Stokes, M., Mather, A.E., 2000. Response of Plio-Pleistocene alluvial systems to tectonically induced base-level changes, Vera Basin, SE Spain. Journal of the Geological Society, London 157, 303-316.
Tankard, A.J., Rogers, J., 1978. Late Cenozoic palaeo-environments on the west coast of southern Africa. Journal of Biogeography 5, 319-337.
Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R., Minter, W.E.L.,

1982. Crustal evolution of southern Africa: 3.8 billion years of Earth history. Springer-Verlag, Berlin, 523 pp.
Törnqvist, T.E. 1998. Longitudinal profile evolution of the Rhine Meuse system during the last deglaciation: interplay of climate change and glacio eustasy? Terra Nova 10, 11-15.
Tyràček, J., 1983. River terraces – important paleoclimatic indicator. In: Billards, O., Conchon, O., Shotton, F.W. (Eds.), Quaternary glaciations in the Northern Hemisphere. IGCP Project 73-1-24. Report No. 9, Unesco International Geological Correlation Programme, Paris, pp. 34-41.
Tyràček, J., 1987. Terraces of the Euphrates River. Sbornik geologickych ved 18,185-202.
Tyráček, J., Westaway, R., Bridgland, D., 2004. River terraces of the Vltava and Labe (Elbe) system, Czech Republic, and their implications for the uplift history of the Bohemian Massif. Proceedings of the Geologists' Association 115, 101-124.
Tyson, P.P., 1986. Climatic Change and Variability in Southern Africa. Oxford University Press, Oxford, 220 pp.
Ubilla, M. 2004. Mammalian biostratigraphy of Pleistocene fluvial deposits in northern Uruguay, South America. Proceedings of the Geologists' Association 115, 347-357.
van den Berg, M.W. 1994. Neotectonics of the Roer Valley rift system. Style and rate of crustal deformation inferred from syn-tectonic sedimentation. Geologie en Mijnbouw 73, 143 156.
van den Berg, M.W., van Hoof, T., 2001. The Maas terrace sequence at Maastricht, SE Netherlands: evidence for 200 m of late Neogene and Quaternary surface uplift. In: Maddy, D., Macklin, M.G., Woodward, J.C. (Eds.), River Basin Sediment Systems: Archives of Environmental Change. Balkema, Abingdon, England, pp. 45-86.
Vandenberghe, J., 1995. Timescales, climate and river development. Quaternary Science Reviews 14, 631-638.
Vandenberghe, J., **this volume**
Veldkamp, A., Buis, E., Olago, D.O., Boshoven, E.H., Marée, M., Gicheru, P.T., Wijbrans, J., 2004. Quaternary fluvial terrace record of Tana River, Kenya. ICGP 449 Final Meeting, Malaga, Spain, Abstract Volume, p. 49.
Veldkamp, A., Buis, E., Olago, D.O., Boshoven, E.H., Marée, M., Gicheru, P.T., Wijbrans, J., In press. Late Cenozoic fluvial dynamics of the Tana river, Kenya, an uplift dominated record. Quaternary Science Reviews.
Wendlandt, E., DePaolo, D.J., Baldridge, W.S., 1993. Nd and Sr isotope chronostratigraphy of Colorado Plateau lithosphere; implications for magmatic and tectonic underplating of the continental crust. Earth and Planetary Science Letters, 116, 23-43.
Westaway, R., 1990. Present day kinematics of the plate boundary zone between Africa and Europe, from the Azores to the Aegean. Earth and Planetary Science Letters 96, 393-406.
Westaway, R., 1998. Dependence of active normal fault dips on lower-crustal flow regimes, Journal of the Geological Society, London 155, 233-253.
Westaway, R., 2001. Flow in the lower continental crust as a mechanism for the Quaternary uplift of the Rhenish Massif, north-west Europe. In: Maddy, D., Macklin, M., Woodward, J. (Eds.), River Basin Sediment Systems: Archives of Environmental Change. Balkema, Abingdon, England, pp. 87-167.
Westaway, R., 2002a. Geomorphological consequences of weak lower continental crust, and its significance for studies of uplift, landscape evolution, and the interpretation of river terrace sequences. Netherlands Journal of Geosciences 81, 283-304.
Westaway, R., 2002b. Long-term river terrace sequences: Evidence for global increases in surface uplift rates in the Late Pliocene and early Middle Pleistocene caused by flow in the lower continental crust induced by surface processes. Netherlands Journal of

Geosciences 81, 305-328.
Westaway, R., 2002c. The Quaternary evolution of the Gulf of Corinth, central Greece: coupling between surface processes and flow in the lower continental crust. Tectonophysics 348, 269-318.
Westaway, R., 2004. Kinematic consistency between the Dead Sea Fault Zone and the Neogene and Quaternary left-lateral faulting in SE Turkey. Tectonophysics 391, 203-237.
Westaway, R., 2006a. Late Cenozoic sedimentary sequences in Acre State, southwestern Amazonia: fluvial or tidal? Deductions from the IGCP 449 field trip. Journal of South American Earth Sciences 21, 120–134.
Westaway, R., 2006b. Investigation of coupling between surface processes and induced flow in the lower continental crust as a cause of intraplate seismicity. Earth Surface Processes and Landforms 31, 1480-1509.
Westaway, R., in press. Late Cenozoic uplift of the eastern United States revealed by fluvial sequences of the Susquehanna and Ohio systems: coupling between surface processes and lower-crustal flow. Quaternary Science Reviews.
Westaway, R., Maddy, D., Bridgland, D., 2002. Flow in the lower continental crust as a mechanism for the Quaternary uplift of south-east England: constraints from the Thames terrace record. Quaternary Science Reviews 21, 559-603.
Westaway, R., Bridgland, D., Mishra, S., 2003. Rheological differences between Archaean and younger crust can determine rates of Quaternary vertical motions revealed by fluvial geomorphology. Terra Nova 15 287-298.
Westaway, R., Pringle, M., Yurtmen, S., Demir, T., Bridgland, D., Rowbotham, G., Maddy, D., 2004. Pliocene and Quaternary regional uplift in western Turkey: The Gediz river terrace staircase and the volcanism at Kula. Tectonophysics 391, 121-169.
Westaway, R., Guillou, H., Yurtmen, S., Demir, T., Rowbotham, G., 2005. Constraints on the timing and regional conditions at the start of the present phase of crustal extension in western Turkey from observations in and around the Denizli region. Geodinamica Acta 18, 313-343.
Westaway, R., Bridgland, D., White, M., 2006a. The Quaternary uplift history of central southern England: evidence from the terraces of the Solent River system and nearby raised beaches. Quaternary Science Reviews 25, 2212-2250.
Westaway, R., Guillou, H., Yurtmen, S., Beck, A., Bridgland, D., Demir, T., Scaillet, S., Rowbotham, G., 2006b. Late Cenozoic uplift of western Turkey: Improved dating of the Kula Quaternary volcanic field and numerical modelling of the Gediz river terrace staircase. Global and Planetary Change 51, 131-171.
Wilson, M., Lyashkevich, Z.M., 1996. Magmatism and the geodynamics of rifting of the Pripyat-Dnieper-Donets Rift, East European Platform. Tectonophysics 268, 65-81.
Wymer, J.J. 1968. Lower Palaeolithic Archaeology in Britain as Represented by the Thames Valley. John Baker, London, 429pp.
Wymer, J.J., 1999. The Lower Palaeolithic occupation on Britain. Wessex Archaeology and English Heritage, Salisbury, 234 pp + 2nd volume of maps.
Young, R.W., Bryant, E.A., 1993. Coastal rock platforms and ramps of Pleistocene and Tertiary age in southern New South Wales, Australia. Zeitschrift für Geomorphologie, N.F. 37, 257-272.
Zeuner, F.W., 1945. The Pleistocene Period: its Climate, Chronology and Faunal Successions (1st edition). Ray Society, London, publication No. 130, 322pp.

Figure Captions

Fig. 1. The Terrace record from the River Rhine; the numbers in circles refer to marine oxygen isotope stages (MIS) during which each terrace aggradation is inferred to have culminated. (a) Longitudinal profile showing terraces of the Middle and Lower Rhine, between the uplifting Rhenish Massif and the subsiding coastal region of the Netherlands. Adapted from Westaway (2001, Fig. 10) and Westaway (2002b, Fig. 6), who listed original sources of information. (b) Transverse profile across the Middle Rhine near Koblenz, showing the transition from a broad floodplain in the Early Pleistocene to a narrow gorge lacking terraces (after Bibus and Semmel, 1977; Westaway, 2002a). Abbreviations: HT – Hauptterrasse (high terrace); MT – Mittelterrasse (middle terrace); NT – Niederterrasse (low terrace); TR – Terrasse (terrace; in the reach upstream of Koblenz).

Fig. 2. Fluvial records from the East European Plain (after Matoshko et al., 2002, 2004): a - location map, showing the key crustal blocks mentioned in the text; b - generalized transverse profile through the Middle–Lower Dniester terrace sediments; c - transverse profile, ~240 km long, across the Middle Dnieper basin, ~100 km downstream of the city of Kiev; d- transverse profile through the deposits of the Upper Don near the city of Voronezh; e - cross-section through the sediments of the Lower Volga, in the region of the Pre-Caspian Block (see part a). Note the contrasting disposition of deposits of particular ages in each case. White numbers in black circles refer to marine oxygen isotope stages to which deposits are attributed. The considerable width of the Middle Dnieper basin (c) means that different deposits overlie different crustal types. For further information and source references see Matoshko et al. (2002, 2004).

Fig. 3. Transverse profiles illustrating fluvial sequences in cratonic regions (after Westaway et al., 2003). Sections a and b are from the cratonic part of peninsular India, being records from the rivers Pravara and Kukadi, respectively. Sections c and d are from the River Vaal, in the Archaean Kaapvaal craton of South Africa: c - after De Wit et al. (1997); d – detail of the younger part of the record, after Helgren (1978). In c, the Wedburg and Proksch Koppie gravels are thought to be Miocene (e.g., de Wit et al., 1997) and the oldest deposit known in the succession, the Nooitgedacht gravel, is thought to date from the Late Cretaceous or early in the Cenozoic (e.g., de Wit, 2004). Of the three 'Younger Gravel' members in d, A and B are thought to be Early Pleistocene, whereas C is biostratigraphically dated to the mid-Middle Pleistocene. In the Riverton Formation, Members I and II have yielded Acheulian artefacts (Middle Pleistocene); Member III has yielded Middle Palaeolithic artefacts, suggesting a late Middle Pleistocene or early Late Pleistocene age; and Members IV and V are Holocene (cf. Westaway et al., 2003). See, e.g., Dingle and Hendey (1984) for further discussion of the Cenozoic evolution of the Vaal river system and Butzer et al. (1973) for more detail on its fluvial deposits.

Fig. 4. The Thames terraces (after Bridgland 1994 with subsequent modifications), showing MIS correlations (? = inferred). a - Idealized transverse section through the terraces of the Middle Thames, ~35 west of London, where the most complete sequence is preserved; b - Idealized transverse section through the terraces of the Lower Thames, ~15km east of London, showing interbedded cold- and warm-climate deposits; this sequence, which begins with the Anglian (MIS 12) glacial diversion of the river, shows optimal preservation of palaeoclimatic evidence. See, e.g., Bridgland and Schreve (2001, 2004) or Bridgland (2006) for details of biostratigraphic and archaeological age-control for these deposits.

Fig. 5. Transverse section through the terraces of the River Somme, in the vicinity of Amiens,

northern France (after Bridgland et al., 2006; Antoine et al., in press), showing MIS correlations (? = inferred).

Fig. 6. Model for terrace formation in response to climatic forcing: a - original model from Bridgland (2000), with downcutting at warming transitions; b - revised model, with downcutting at both warming and cooling transitions (after Bridgland, 2001); c - third possible scenario, newly added here, with downcutting at cooling transitions to match rivers such as the Somme (Fig. 5; see text).

Fig. 7. Schematic transverse profile through the staircase of terraces of the lower River Aguas in the Vera Basin, SE Spain (adapted from Schulte et al. (2000); Schulte (2002)). Inferred MIS correlations are shown.

Fig. 8. Comparison of uplift rates deduced from different terrace records: (a) and (b) long-timescale (post-3.5 Ma) and short timescale (post-1.3 Ma) records for the Middle Thames ~45km west of London, after Westaway et al. (2002; cf. Fig. 4a). (c) and (d) long- and short timescale records for the Somme at Amiens (Fig. 5). (e) and (f) long- and short timescale records for the Middle Rhine at Andernach (Fig. 1). (g) long-timescale (7.5 Ma) record from the Aguas (Fig. 7), also including the Early Messinian, Early Pliocene and Pleistocene marine sediments in the same region; (h) long-timescale (6 Ma) record from the Middle Dniester (Fig. 2b). Modelling solutions use the technique of Westaway (2001; Westaway et al., 2002); see also Westaway (2002a, c). Filled symbols indicate preferred fits between observed terrace heights and model predictions; open symbols indicate other possible ages for individual river terraces. All solutions assume κ (thermal diffusivity of the crust) 1.2 mm^2 s^{-1}.
Model parameters are: W_i=z_i-z_b, where z_i is the depth at which the lower-crustal flow is concentrated and z_b is the depth of the base of the brittle upper crust (Westaway, 2001; Westaway et al., 2002), which is taken at the temperature threshold T_b=350°C. u is the geothermal gradient in the lower crust. ΔT_e and t_o are the magnitude and start timing of each phase of LCFF (see Westaway et al., 2002, for full explanations). For the viscosity parameterization used for the mobile lower crust, with a temperature-dependent linear viscous rheology, and for an assumed uniform steady-state geothermal gradient, the depth z_i is roughly 9/10 of the way down from z_b to the depth z_m of the Moho (Westaway, 1998). As noted previously (e.g., Westaway, 2002b), the thicker the mobile lower-crustal layer is assumed to be, the larger W_i is, and thus the more sluggish is the predicted uplift response to a given phase of lower crustal flow forcing (LCFF). (a) and (b) use W_i=8 km, u=10 °C km^{-1}, t_{o1}=18 Ma, ΔT_{e1}=-6.0 °C, t_{o2}=3.1 Ma, ΔT_{e2}=-3.4 °C, t_{o3}=0.9 Ma and ΔT_{e3}=-2.0 °C. Observed uplift is measured relative to the present-day river level of 18 m a.s.l., except for the marine Red Crag deposit, the present-day altitude of which used to indicate uplift since its deposition (i.e., palaeo-water depth and any fall in global sea-level are both neglected). (c) and (d) use W_i=9 km, u=20 °C km^{-1}, t_{o1}=18 Ma, ΔT_{e1}=-6.0 °C, t_{o2}=3.1 Ma, ΔT_{e2}=-2.9 °C, t_{o3}=0.9 Ma and ΔT_{e3}=-2.9 °C. Reference level used for measuring uplift is +2 m, a.s.l., 1 m below the top of the Valley Bottom gravel. (e) and (f) use W_i=10 km, u=20 °C km^{-1}, t_{o1}=18 Ma, ΔT_{e1}=-9.0 °C, t_{o2}=3.1 Ma, ΔT_{e2}=-4.5 °C, t_{o3}=0.9 Ma and ΔT_{e3}=-11.5 °C. Observed uplift is measured from a reference level of 67 m a.s.l., 7 m above the present river level. (g) uses W_i=11 km, u=20 °C km^{-1}, t_{o1}=18 Ma, ΔT_{e1}=-10.0 °C, t_{o2}=6 Ma, ΔT_{e2}=-16 °C, t_{o3}=3.1 Ma, ΔT_{e3}=-2 °C, t_{o4}=0.9 Ma and ΔT_{e4}=-3 °C. To convert fluvial incision to uplift, a channel lengthening correction of +100 m has been applied linearly between 3100 ka and 950 ka (MIS 25). Observed uplift is measured from a reference level 3 m above present river level (for river terraces) and from present sea-level (for marine terraces). (h) uses W_i=8 km, u=20 °C km^{-1}, t_{o1}=18 Ma, ΔT_{e1}=-22.0 °C, t_{o2}=5.7 Ma, ΔT_{e2}=-1.5 °C, t_{o3}=3.1 Ma, ΔT_{e3}=-0.7 °C, t_{o4}=2.0 Ma, ΔT_{e4}=-2.2 °C,

t_{o5}=0.9 Ma and ΔT_{e5}=-3.7 °C. Observed uplift is measured from 1 m below the present river level at Serebriya, Ukraine, which is 60 m above the level of the Black Sea. The top of the Sarmatian 'marine' sediment is at ~330 m a.s.l., which is assumed to represent ~300 m of uplift and ~30 m of eustatic sea-level fall. This sediment is assumed to have an age of 10.6 Ma, at the Sarmatian-Meiotian boundary. To link this to the later fluvial record, a 60 m channel-lengthening correction is applied at a uniform rate between 10.6 Ma and 5.3 Ma.

Fig. 9. The sequence in the Upper Orontes valley: **(a)** Location map; **(b)** Idealized transverse section through the Orontes terraces in the Homs area (modified from Bridgland et al., 2003). Bases of terraces and other field relations are shown dashed if not directly observed. Numbers in circles indicate MIS correlations. Terrace and archaeological evidence from the Middle Orontes (Besançon and Sanlaville, 1993; Dodonov et al., 1993; Muhesen, 1993) is shown, for comparison, to the left of the main staircase. There has been ~400 m of total incision by the Orontes since the eruption of the Homs Basalt, which took place in the latest Miocene (Messinian; ~6-5 Ma; see Westaway, 2004 for a summary of the dating evidence).

Fig. 10. Representative transverse profile across the terraces of the River South Platte, near Denver, Colorado (modified from Osterkamp et al., 1987), showing MIS correlations (? = inferred). Age constraints are from Osterkamp et al. (1987), as amended by Gansecki et al. (1998), Lindsey et al. (1998), Dethier et al. (2001), Schildgen et al. (2002) and references cited therein. The start of incision below the level of the 'Late Miocene / Early Pliocene' erosion surface can be dated to ~5 Ma from the end of deposition, in adjacent regions, of sediment (of the Ogallala Group) that is derived from this erosion (e.g., McMillan et al., 2002). The Nussbaum terrace gravel is correlated with other deposits (e.g., the Blanco Formation of the southern High Plains) with a fauna sssigned to the Blancan mammal assemblage zone. Correlative sites underlie calcrete capped by the Guaje ash, from the ~1.6 Ma eruption of Valles Caldera in New Mexico. This gravel thus probably dates from the early Early Pleistocene. The Rocky Flats terrace gravel, of 'Nebraskan' age, is capped by well-developed palaeosol thought to record at least two interglacials. It is tentatively dated to ~1.35 Ma from the extent of soil development and to up to ~1.5 Ma using cosmogenic ^{10}Be; it probably represents the later part of the Early Pleistocene. The deposits of the Verdos terrace contain ash from the 602±4 ka Lava Creek B eruption of Yellowstone, with a well-developed 'Yarmouth' palaeosol. The gravel forming this terrace thus probably aggraded during MIS 16. The deposits of the Slocum and Louviers terraces have yielded uranium series dates on bone of 190±50 ka and 129±10 ka, respectively. Both are capped by palaeosol characteristic of the Sangamon (MIS 5e) interglacial. The gravels forming these terraces thus probably aggraded during MIS 8 and MIS 6, respectively. The deposits forming the Broadway terrace date from the Pinedale (MIS 2) glaciation. Those of the Piney Creek alluvium are Holocene, and those of the post-Piney Creek alluvium are late Holocene, with radiocarbon dates of <1 ka.

Fig. 11. Idealised transverse profile through the terrace staircase of the Colorado River and its major tributary, the Gunnison, in the vicinity of Grand Junction, Colorado. Numbers in circles are interpreted MIS correlations. Data have been derived from localities up to ~150 km apart, compiled from the following sources (see Fig. 12): Hansen (1987), Baker et al. (2002), Bryant et al. (2002), Scott et al. (2002), Garhart et al. (2003), Kellogg (2004) and Karlstrom (2005). Numerical ages are from Ar-Ar dating. Note phases of major incision in the Late Miocene, in the Late Pliocene and starting in the early Middle Pleistocene. There is of course no guarantee that in the earliest of these phases, incision served as a direct proxy for uplift; early in the development of other large river systems, incision significantly exceeded contemporaneous uplift (e.g., Westaway, 2002b). The possible association of the ~600 ka Yellowstone Lava

Creek B ash with the 250 m Colorado terrace is the highest of a range of possibilities indicated by Karlstrom (2005); this ash may correlate in his view with as recent a terrace as that at 190 m, whereas according to Scott et al. (2002) its equivalent may be the 165 m terrace.

Fig. 12. Modelling solution for the uplift history revealed by the Colorado River system in the vicinity of Grand Junction, Colorado. Altitudes above the present river level are converted directly to estimates of uplift. Model prediction, using the same technique and notation as Figure 8, is based on the following parameter values: W_i=6 km, u=10 °C km^{-1}, κ=1.2 mm^2 s^{-1}, t_{o1}=18 Ma, ΔT_{e1}=-1.0 °C, t_{o2}=10 Ma, ΔT_{e2}=-11.6 °C, t_{o3}=6 Ma, ΔT_{e3}=+1.2 °C, t_{o4}=3.1 Ma, ΔT_{e4}=-7.2 °C, t_{o5}=2.5 Ma, ΔT_{e5}=+4.2 °C, t_{o6}=2.0 Ma, ΔT_{e6}=-2.2 °C, t_{o7}=1.2 Ma, ΔT_{e7}=+1.0 °C, t_{o8}=0.87 Ma, and ΔT_{e8}=-7.5 °C. **(a)** Uplift history since 11 Ma. **(b)** Enlargement showing the record since 3.5 Ma. **(c)** Enlargement showing the record since 1.4 Ma. **(d)** History of variation of uplift rate. Sources of data are indicated. The possible alternative correlations of the Yellowstone Lava Creek B ash with Colorado terraces, indicated in Figure 11 caption, would necessitate lower values of W_i to account for the high rates of incision and uplift required in the early Middle Pleistocene.

Fig. 13. Terraces of the River Sundays, South Africa: (a). location map (b). Schematic transverse profile across the terrace staircase at Kirkwood, Eastern Cape province, South Africa (modified from Hattingh and Rust, 1999). Suggested MIS assignments are shown, based on incision/uplift modelling (see Fig. 14).

Fig. 14. Uplift modelling of the Sundays terrace staircase at Kirkwood, as illustrated in Figure 13b, and of the staircase of marine terraces bounding the adjacent Indian Ocean coastline. Inferred MIS correlations are shown. Observed uplift is measured from present river level, which is 50 m above sea-level. A +50 m correction has been applied to Sundays terrace T1 to account for post-depositional downstream channel lengthening. Display format is the same as in Figure 8, except round symbols mark marine deposits. Marine terraces (after Hattingh and Rust, 1999) are labelled with M followed by the height a.s.l. in metres; thus M240 means the ~240 m a.s.l. terrace. Prediction uses W_i=8 km, u=20 °C km^{-1}, κ=1.2 mm^2 s^{-1}, t_{o1}=18 Ma, ΔT_{e1}=-10.0 °C, t_{o2}=3.1 Ma, ΔT_{e2}=-11.2 °C, t_{o3}=0.9 Ma and ΔT_{e3}=-5.5 °C. (a) Observed and predicted uplift histories since the Middle Pliocene. (b) Enlargements of part (a), showing the Middle and Late Pleistocene in greater detail. (c) Predicted variations in uplift rate.

Fig. 15. Schematic transverse profile across the terrace staircase of the River Shoalhaven at Larbet, New South Wales, SE Australia (modified from Nott et al., 2002). Inferred MIS correlations are shown

Fig. 16. Idealized transverse sequence through the terraces of the River Acre, western Brazil. Based on data from Westaway (2006b). Age constraint is poor but the low terrace probably dates from MIS 2.